Fuel consumption of timber harvesting systems in New Zealand

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By

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Abstract

Fuel is a major cost in logging and is also relied on by logging contractors in New Zealand to adjust unit logging rates in dollars per cubic metres ($\$/m^3$). There is however, no benchmark on fuel consumption rates in litre per cubic metres (l/m^3) in New Zealand, making it difficult to optimise logging operation during planning. A study on fuel consumption of timber harvesting systems in New Zealand was conducted with the participation of 17 ground-based (GB) and 28 cable yarding (CY) logging contractors with crews working commonly on pine plantations (*Pinus radiata*). The logging contractors, distributed in both the North and the South Islands of New Zealand, provided data on fuel use, production, stand and terrain attributes, type and number of machines used by month or year of harvesting. This data was used to determine and set benchmark on rates of fuel use in l/m^3 and litres per kilowatt-hour (l/kWhr), and establish the proportion of unit fuel consumption costs in unit harvesting costs by type of harvesting system.

All the GB systems combined harvested approximately 1.1 million cubic meters of timber using 2.94 million litres of fuel. Similarly, all the 28 CY systems combined harvested approximately 1.5 million cubic metres by consuming 4.6 million litres of fuel. Results showed that on average, the rates of fuel use for GB systems combined was 3.04 l/m^3 and 0.15 l/kWhr, while that of CY systems was 3.18 l/m^3 and 0.09 l/kWhr. There was no clear difference in average rates of fuel use in l/m^3 between GB and CY unlike rates of use in l/kWhr. Using comparable data from GB systems in the Southern US states of Alabama, Georgia, Florida, Louisiana, and North Carolina, on average, GB systems in New Zealand use 32% more fuel per unit of production. Sensitivity analyses based on unit harvesting rates ($\$/m^3$) from harvesting benchmarking data and average fuel (diesel) prices for 2013 in New Zealand showed that fuel costs per unit volume of wood harvested, on average, constitutes 16 and 14% for GB and CY operations, respectively per unit cost of harvesting.

The study concluded that on average, GB and CY harvesting systems use the same rates of fuel use in l/m^3. The rates of fuel use in l/m^3 were found to be dependent on total production, slope of harvesting sites and directions of pulling during extraction. The results of the study also showed that GB and CY harvesting systems use different rates of fuel in l/kWhr. The rates of fuel use in l/kWhr were found to be dependent on the type of harvesting system used, total production, number of machines used, average power, slope, directions of pulling during extraction and surface moisture conditions during harvesting.

The results of this study will contribute significantly to the understanding of logging fuel use by providing a benchmark on rates of use in l/m^3 and l/kWhr, for harvesting planning, adjustment of logging rates, and updating the existing machine costing spreadsheet. The rates of fuel use in l/m^3 reported in this study will also be applicable in comparing operational costs between harvesting systems and machines for purposes of economic efficiency.

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Chapter 1: Introduction

In the New Zealand context, forestry products contribute approximately 3% of gross domestic product (GDP) generating approximately $4.7 billion (NZD) of export earnings annually (NZFOA, 2012). The annual harvested log volumes are projected to increase from the current 27 to 35 million cubic metres by 2023 (NZFOA, 2012). This predicted increase timber harvesting activities by logging contractors will result in an increase in the use of logging machinery and, by extension, fuel use by machines during the harvesting operations. This therefore requires logging managers to make optimised decisions on available machines and selected harvesting systems using information on fuel consumption rates, especially for new harvesting sites. Harvesting greater volumes of wood at higher rates of fuel use may not effectively translate to economic gains due to variability in fuel prices. Variability in fuel prices affects the proportion of fuel costs in unit harvesting cost. This further limits profit margins expected by logging contractors, because fuel prices are affected by externalities, such as inflation, that are beyond the control of logging managers.

The cost of fuel used during logging operations account for between 15 and 20% of unit harvesting cost in Southern US (Greene, Biang, & Baker, 2014), 10% in Canada and 20% in Sweden (Nordfjell, Athanassiadis, & Talbot, 2003), making it a highly variable input cost component in logging. This high variability in fuel costs is of concern to logging contractors due to the uncertainty it presents to profitability gains. Understanding the proportion of fuel costs in unit harvesting rates is difficult due to the way it is measured and reported. Logging fuel consumption has been measured and expressed in litres per scheduled machine hour (l/SMH) (Holzleitner, Stampfer, & Visser, 2011; Jiroušek, Klvač, & Skoupý, 2007), litres per productive machine hour (l/PMH) (Gordon & Foran, 1980), and in litres per kilowatt-hour (l/kWhr) (Alastair, 1994; Holzleitner et al., 2011). Expressing rates of fuel use with units of time element as the denominator does not allow for the determination of cost proportion of fuel in harvesting cost.

Monetary values for the units of time element cannot easily be determined because production is typically the measured/recorded output with regards to harvesting (Sundberg & Svanqvist, 1987). Internationally, most logging contractors concentrate on meeting production targets as a measure of operational efficiency (Pokorny & Steinbrenner, 2005). Comparatively less attention has been paid to the rates of fuel used by machines than to entire harvesting operation costs to produce a given volume of wood. Furthermore, most logging contractors do not know, or have very little information on, fuel consumption rates per unit of production of timber specific to the harvesting systems and machines they use in New Zealand. For example, results on logging fuel use research conducted in New Zealand by Karalus (2010) and Amishev (2010) on behalf of future forests research (FFR), and by Gordon and Foran (1980) through logging industry research organisation (LIRO), are only accessible to logging contractors affiliated with these research organisations. This makes accessibility of the findings on rates of fuel use difficult for planning and management purposes, and further hinders a better understanding on rates of logging fuel use by machines and harvesting systems, along with key drivers of their variability.

The primary harvesting operations of felling, extraction, processing, and loading are conducted by logging crews under varied forest settings, with distinct stand and terrain variables, using machines that vary with type, make, and power ratings (Jiroušek et al., 2007). More importantly, the constantly changing harvesting scenarios such as moving a crew to a new stand, acquiring new and more specialised harvesting machines, the need to train and equip operators with new operational skills, and responding to unplanned demands from logging contract providers can make it difficult to track fuel use. Therefore understanding fuel consumption rates by a given harvesting system and machines, and how these rates of fuel use are influenced by changing harvesting site terrain and stand factors is important for optimised decision making and operational efficiency to logging contractors, forest management companies, and landowners for planning purposes. This also provides the logging stakeholders with a benchmark for adjusting logging rates in the event of sudden change in fuel prices in the existing logging contract.

This study aims to collect data on fuel consumption and production by machines and harvesting systems commonly used in New Zealand through a survey of logging contractors. With data on production and fuel use by logging crews, the study aims to determine the average rates of fuel consumption per unit volume of wood harvested (l/m^3) and per kilowatt-hour (l/kWhr), and set them as benchmark under harvesting conditions specific to New Zealand. The study also aims to establish significant differences in rates of fuel use between harvesting systems and their variability with harvesting site factors. Fuel consumed during secondary transportation of processed and graded logs to the customers is beyond the scope of this study.

1.1 Overview of timber harvesting operations

Logging operations are executed by logging contractors on behalf of private tree growers and forest growing companies who aim to generate revenue from capital investment on the production forests upon sales. Logging operations begin with tree felling at the stump site, followed by primary transportation or extraction of felled stems to landings for processing into various log grades, and ends when the processed logs are loaded onto log trucks in readiness for secondary transport to mill, port facility or wharf (Visser, 2007; Visser, McDonagh, Meller, & McDonald, 2004). These major steps in the harvesting operations require the use of various machines designed to perform multiple operational functions specific to each phase of timber harvesting (Spinelli, Owende, & Ward, 2002). These harvesting operations are conducted either by ground-based (GB) or cable yarding (CY) harvesting systems which are chosen based on site slope and method of extraction in New Zealand (Visser, 2010). More importantly, these harvesting operations are carried out by machines that use fossil fuel in the form diesel or petrol to power them mechanically. Fuel consumption needs by individual machines during harvesting operations vary according to work functions, end product requirements, machine type and power rating (Makkonen, 2004). A brief overview of main logging processes and phases are outlined in the sections that follow.

Felling

There are two most common methods of tree felling, namely motor-manual and mechanised. Motor-manual felling involves the use of motor operated chainsaws while mechanised felling is done by specialised machines such as harvesters or self-levelling feller-buncher machines (Kellogg, Bettinger, & Studier, 1993). Motor manual chainsaw is commonly used for felling due to its low fuel consumption and versatility in difficult terrains (Spinelli, Ward, & Owende, 2009), and their low weight and portability making it easier for the operator to manoeuvre in difficult terrain (Visser, 2011). However, the use of chainsaws requires that additional fuel be carried in a separate fuel container for refuelling during operations and places workers in close proximity to felling action. Currently in New Zealand, there is a general shift towards full mechanisation of logging operations, regardless of any potential increase in fuel consumption, due to increased concerns for worker safety (Visser, Raymond, & Harrill, 2014). Fuel consumption by felling machines varies with type of operation, whether manual or mechanised (Sambo, 2002), with the specialised felling machines such as feller-bunchers and harvesters using more fuel, given their level of automation, engine size, and additional work functions compared to motor-manual chainsaws (Janett, 1986).

Extraction

Extraction, also known as primary transportation, involves moving felled stems or logs from the growing/stump site to landings (Visser, 2007). Extraction can be done through aerial or suspension systems by employing the use of various cable yarding configurations commonly known as cable logging systems (Harrill & Visser, 2012), or by tractive systems involving skidding the stems on the ground or forwarding them in bunks, commonly known as ground-based system. The choice of extraction method is dependent mainly on slope, soil moisture conditions and stability, extraction distances, and harvest setting configuration (Dash & Marshall, 2011; Visser, Spinelli, & Magagnotti, 2011).

Cable yarding of logs or stems begins when the carriage, attached to a hauler or yarder machine, is released (outhaul). The carriage is then lowered for picking (hooking) of stems or logs. The loaded carriage then travels back to the landing with stems (inhaul) and ends when the stem or logs are dropped (unhooked) at a landing or roadside. During inhaul, the stems or logs are partially or wholly suspended from the ground. Similarly, ground-based extraction by skidding involves dragging of stems with butt end partially suspended from the ground by the use of either cable or grapple skidders.

Skidding begins when a skidder machine starts driving from a landing or roadside to the stump or felling point empty (outhaul), picks or hooks the felled stems or logs (loading), drives back to a landing loaded, and ends when the stems or logs are off-loaded or dropped at the landing. Work functions such as outhaul, loading, and inhaul during extraction determines the system cycle time, and require the use of fuel by machines involved at different rates depending on the type of rigging configuration used, extraction distance involved, and the cycle time.

Processing

Processing during logging involves decision making based on cut-plans defining different log grades to be produced depending on customer specifications (Tolan & Visser, 2015). Processing involves topping, delimbing, debarking, bucking, and ends when the final log grade is piled into log assortments of similar grades. All these successive activities consume fuel at different rates during processing. Log processing can be motor-manual or mechanised depending on scheduled end product requirements and target production (Visser, 2013). Motor-manual processing of logs is done with chainsaws while mechanised processing involves the use of specialised equipment such as a processor machine or processing head attached to a base machine (e.g. an excavator).

Chipping/grinding

In operations where chipping or grinding is part of harvesting, a chipper or grinding machine is often used to manage slash or chip end-cuts, stems, and logs considered poor for structural log grade quality material at a landing (Spinelli, Hartsough, & Magagnotti, 2005), and wood chips produced transported to pulp mills or bioenergy power plants. Fuel consumption by chipper machine depends on chipper workload (infeed material), the quantity of chipping material on a landing, size of the chipping material, operator experience, and duration of chipping (Spinelli, Ivorra, Magagnotti, & Picchi, 2011). Having chipper machine at a landing is energy intensive and requires a constant fuel supply schedule due to increased material handling, and fuel used during chipping/grinding has the potential of increasing harvesting costs if considered as part of total harvesting production.

Other landing activities

Several activities other than processing; fleeting, sorting, grading, and loading of log trucks, are also conducted on landing. These activities require proper planning and execution in terms of machine selection, safety, ergonomics, and require landing layout to be sizable enough to accommodate all the activities planned (Visser et al., 2011). These activities are part of wider harvesting operations and require proper fuel supply planning strategy to ensure operational efficiency. A combination of a front-end loader, knuckle-boom loader, and an excavator fitted with grapple are commonly used in a single landing. These machines use fuel at different rates depending on payloads and daily production targets, and therefore require adequate planning on fuel supply. Visser (2010), found that 79% of loading and fleeting activities are performed by front-end loaders while use of knuckle boom loader accounts for only 21% of the activities in a single landing where both machines are scheduled to work. Differences in durations of work by machines performing similar tasks are possible indicators of variability in rates of fuel consumption.

1.2 Harvest planning

Timber harvesting is both intensive and extensive given the number of operations involved and, therefore, requires optimised decision making in terms of labour, machinery, and energy requirements (Spinelli et al., 2002). For example, economic and technical constraints specific to a logging crew may require a reduced number of machines to minimise harvesting costs associated with high levels of energy use (Athanassiadis, 2000). As a consequence, harvesting managers are required to make optimal decisions during logging planning guided by knowledge on fuel consumption and factors contributing to variability in rates of fuel use (Spinelli et al., 2009). Information on rates of fuel use have also been adapted in models developed for decision making criterion for selection and ranking of various harvesting systems, based on variable cost of fuel use to achieve economic viability in Western Australia (Ghaffariyan & Brown, 2013). In Swedish forestry, understanding the rates of logging fuel use has enabled logging researchers to impart the concept of optimised efficiency to logging contractors (Lindholm & Berg, 2005), by demystifying the gains made through logging mechanisation on reduced fuel consumption rates. Lindholm and Berg (2005), also reported that logging operations are the highest fossil fuel consumer in forestry, in comparison to forest plantation establishment and siliviculture, and observed that effective monitoring and control of fuel consumption rates minimises operational costs

Logging contractors and managers in New Zealand are tasked with selecting between GB or CY harvesting systems and machines for new harvesting sites, with consideration to the uniqueness of its plantation forest landscapes. Knowledge on logging fuel consumption is important to harvest plan for decision making when planning for new harvesting sites. For example, this includes (a) decision making about harvesting system selection for given sites under varying slope and stand attributes, (b) allocating machines to most suitable working site conditions (c) the future impact on fuel cost when harvesting on more remote and steep forests, (d) setting unit logging rates, and (e) the effect of short term inflation in fuel prices and its impact on unit harvesting costs. Such decisions when made appropriately help meet set company goals by ensuring that operations are optimised in terms of labour input and that machines are matched appropriately with the selected harvesting system (Spinelli et al., 2002). Information on fuel consumption rates during logging is also useful to logging contractors when adjusting for unit logging rates ($/m^3) when prices change across the year (Figure 1).

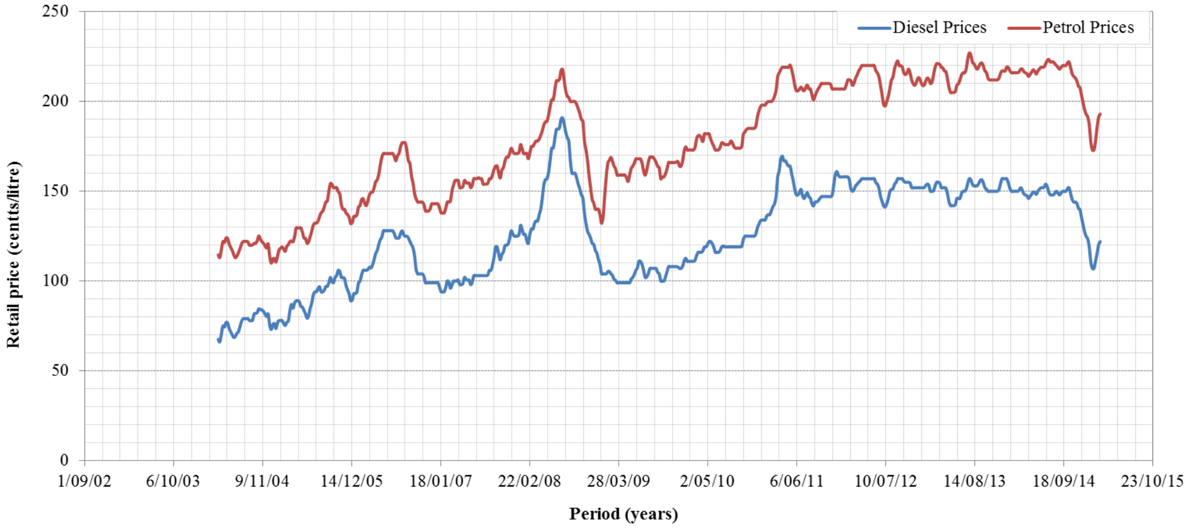

Figure 1: Weekly oil price monitoring (New Zealand Ministry of Business Innovation and Employment, NZMBIE, 2015)

1.3 Problem statement

Logging in forestry has evolved over the years from use of animals to mechanisation through the use of more complex and heavy machinery (Harrill & Visser, 2012). Logging mechanisation resulted from increased safety concerns and technical efficiency (Visser et al., 2014). The advent of new technology in engine development has made fuel use data from old machines obsolete for harvesting planning purposes. In the logging industry, competition for common log markets (e.g. China), reliance on fossil fuel from common suppliers (e.g. the Middle East), non-static global fuel prices, and inflation require logging contractors to have a common benchmark for rates of fuel use for the purposes of comparing harvesting costs. Moreover, global climate change policies also require developing and developed countries to reduce carbon emissions into the environment. Forestry logging operations, given the use of fossil fuels by machinery used, is a contributor to greenhouse gases into the environment and thus contributes to climate change.

The logging industry is, however, a complex business entity to invest in and faces a range of problems regarding energy consumption due to changes in technology, market competition, need for optimised efficiency, and growing concerns over increased carbon emissions from fossil fuels. Forestry logging operations are also conducted under constantly variable slope and stand characteristics that are assumed to affect rates of fuel consumption by machines and harvesting systems (Nordfjell et al., 2003). This complexity has made it increasingly difficult for loggers over the years to document fuel use as most rely on production as a measure of operational efficiency (Athanassiadis, Lidestav, & Wästerlund, 1999; Smidt & Gallagher, 2013). Published fuel use research indicates that logging contractors seem to have limited knowledge of how much fuel they use during harvesting due to lack of fuel use and production records, coupled with an absence of a proper fuel use monitoring mechanism (Athanassiadis et al., 1999). However, it is possible to keep records of fuel used during logging operations (Kenny, Thomas Galagher, Smidt, Dana Mitchel, & McDonald, 2014), by adopting any method of fuel estimation and recording recommended by Acuna et al. (2012) in good practice guidelines for biomass production.

Differences in common denominators used in reporting rates of fuel use in forestry logging also hinder direct economic comparisons of similar machines and harvesting systems operating under similar harvesting site conditions. Over the years, rates of logging fuel use have been reported using different units of measure. For example, litres per scheduled machine hour (l/SMH), litres per productive machines hour (l/PM, litres of fuel per kilowatt-hour (l/kWhr), litres of fuel per unit volume of production (l/m^3) and/or litres of fuel per unit weight of machine used (l/tonne) have been preferred by different authors when reporting logging fuel consumption in different countries of data collection and research.

Reporting rates of fuel use per unit of production provides a robust measure of operational costs and allows for monetary comparison between harvesting systems and machines used as opposed to reporting the rates of use in l/kWhr. Reporting rates of fuel use relative to PMH, SMH and/or kWhr, renders economic interpretation and comparison between harvesting systems and machines difficult as it is not easy to assign economic value of machine per SMH, PMH or kWhr of operation unless productivity output is involved. Existing logging costing spreadsheets provided in the New Zealand Business Management for Logging handbook (Alastair, 1994) provide benchmark rates of fuel use in l/kWhr for GB and CY operations for unit machine costing purposes without taking into consideration harvesting system and productivity.

The need to use unit volume of production (m^3) as a relative measure and common denominator for reporting the rates of fuel use for purposes of economic comparison has seen recent fuel use studies across the southern states of the USA, Sweden, and Canada report their logging fuel use rates per unit of production (l/m^3) (Athanassiadis, 2000; Athanassiadis et al., 1999; Greene et al., 2014; Kenny et al., 2014; Sambo, 2002) (Klvac & Skoupy, 2009). Using unit of production as a common denominator for fuel consumption is also important as a benchmark for setting logging rates, as most forestry companies in New Zealand adjust their logging rates based on fuel consumption and costs to harmonise the effects of high pump prices.

Global fuel prices are influenced by forces of inflation in the energy markets which are beyond the control of logging contractors and stakeholders in this industry. In the event that fuel prices suddenly change, knowledge of rates of fuel use in l/m^3 by harvesting systems and machines would allow logging contractors to determine how much their total harvesting cost would change. This would further help them explore avenues of optimising their harvesting operations under the fundamental economic principle of minimising input costs of production (Hackman, 2008). Moreover, rates of fuel use affect the proportion of fuel costs in harvesting cost, for example, the cost of fuel used during harvesting constitutes 10% of total harvesting cost in Canada and 20% in Sweden (Nordfjell et al., 2003). Fuel costs also constitute between 15 – 20% in Southern USA according to Greene et al. (2014), a variability that makes profitability forecast in logging industry difficult to most contractors.

In summary, knowing rates of fuel use for any logging operation by ground-based and cable yarding harvesting systems and by machines provides logging contractors with a benchmark for planning and cost monitoring in a similar manner to machine costing spreadsheets (Alastair, 1994) and annual benchmarking data (Visser, 2011, 2013, 2015) in New Zealand. Therefore, properly captured and recorded fuel use and production data allows for optimisation of harvesting operation and selection of harvesting systems and machines for new harvesting sites. Furthermore, such data provides useful information when adjusting unit logging rates under changing fuel prices without compromising social acceptability, economic viability, and technical efficiency of logging operations (Sundberg & Silversides, 1988).

1.5 Research objectives, questions and hypotheses

This study aims for a more general objective of reviewing published literature on previous and current fuel use studies to establish temporal and spatial frequency. Through review of published fuel use research, this study also aims to identify existing gaps that require further studies to boost the understanding of stakeholders in logging industry on logging fuel use, for system and machine selection for decision making and planning.

Specifically, this study aims;

1) To determine and compare rates of fuel consumption in l/m^3 and l/kWhr between ground-based and cable yarding harvesting systems used under harvesting conditions specific to New Zealand.
2) To set benchmark rates of fuel use for ground-based and cable yarding operations as standard for selection of harvesting systems and appropriate machines for new sites.
3) To determine the proportion of fuel costs in unit harvesting cost using the benchmark rates of fuel use in l/m^3 from this study and unit logging rates from annual harvesting benchmarking data.
4) To compare the rates of fuel use in l/m^3 for ground-based harvesting systems in New Zealand to similar ground-based systems in the Southern US and establish causes of variability.

These specific objectives are hoped to be achieved through answering the following research questions and, by verifying the underlying hypotheses;

A) Do New Zealand ground-based and cable yarding harvesting systems use fuel at the same rates (in l/m^3 or l/kWhr) during logging operations, irrespective of machine selection and harvesting site factors?

This question tests the ***null hypothesis*** that the average rates of fuel consumption are the same irrespective of harvesting system chosen, machines used, and prevailing harvesting site factors.

B) Are there clear differences in average rates of fuel consumption (in l/m^3 or l/kWhr) between ground-based and cable yarding systems harvesting under New Zealand conditions given the differences in machines used and variability in harvesting site factors?

This second question tests the ***alternative hypothesis*** that the average rates of fuel used during harvesting, between ground-based and cable yarding harvesting systems, is different due to differences in harvesting site factors and machines used.

1.4 Justification

This research seeks to demystify logging fuel use to logging contractors, forest growing companies and landowners. The research focuses on reporting rates of fuel relative to unit of production (l/m^3) and also in l/kWhr as benchmark for New Zealand. Having rates of fuel use reported in l/m^3 allows for monetary comparisons of operational costs between machines and harvesting systems and further facilitates machine and harvesting system selection and allocation for new harvesting sites. Having benchmark on rates of fuel use in l/m^3 allow logging contractors to monitor and control of fuel consumption with a view to optimise operational costs for purposes of economic viability. Moreover, since fuel prices are not easy to control due to inflation, benchmark on rates of fuel use in l/m^3 can also be used by logging contractors as indicators of economic efficiency by knowing how much harvesting costs will change with changes in fuel prices. In acknowledging that logging contractors in New Zealand fully rely on fuel price changes to adjust unit logging rates ($\$/m^3$), there is however, no benchmark for such adjustment yet fuel prices keep changing. Therefore, benchmark rates of fuel use in l/m^3 from this study will significantly assist logging contractors in adjusting unit logging rates ($\$/m^3$) when fuel prices change. Benchmark rates of fuel use in l/kWhr from the study can also be used to update machine costing schedule currently in use in New Zealand, as this costing model is based on data from old machinery.

Knowledge on rates of fuel use will also allow logging contractors to understand how differences in terrain and stand characteristics of harvest sites contribute to variability in average rates of use. The study will provide logging contractors with the opportunity to know whether different types of logging systems use different rates of fuel per unit of production. Informed logging contractors are better placed to understand and relate how changing fuel prices will affect harvesting costs and profitability. Results of this study will also contribute to expanding the decision making and planning horizon of logging contractors on drivers of average rates of fuel use and its variability, and also by providing them with benchmark on rates of fuel use for selection of harvesting systems and machines for new harvest sites.

1.7 Thesis structure

This has been organised in six chapters.

Chapter 1 gives general introductory information and an overview of timber harvesting operations and planning. The chapter also states the research problem and why it is necessary, including its aims and objectives to be met through answering key research questions and hypotheses.

Chapter 2 reviews published literature on fuel consumption in various aspects relating to methods of estimation and units of measure; harvesting systems of New Zealand and factors affecting fuel consumption; logging machinery, mechanisation, productivity and operational efficiency; emission associated with logging fuel use; logging costing models and proportion of fuel in harvesting costs. The chapter further narrows down fuel use research scenario in New Zealand by giving a summary of identified gaps in fuel use research.

Chapter 3 presents the various approaches and methods used to meet the objectives of this study.

Chapter 4 presents the results obtained from the survey and statistical analyses performed, with more focus on rates of fuel use in New Zealand. This chapter also presents comparisons on rates of fuel use in New Zealand made with data in the literature and rates of fuel use from Southern US ground-based systems.

Chapter 5 discusses key findings on rates of fuel use and their variability comparatively with published research.

Chapter 6 concludes the study by answering research questions and hypotheses to justify its aims and objectives. The chapter also presents study limitations and suggests areas for further research in logging fuel consumption and productivity.

Chapter 2: Literature review

This section presents a review of published research on fuel use during logging operations and their occurrences, on temporal and spatial scales. The information presented in this review is aimed at improving our understanding of operational efficiencies associated with logging fuel use for possible application by stakeholders in logging industry. This review is also important as the information presented of fuel use is expected to form the basis for harvesting systems and machine selection during decision making and planning for harvesting operations. The relevance of this general review of logging fuel use has been narrowed down to logging fuel use in relation to common harvesting systems, logging machinery, productivity, mechanisation and operational efficiency.

Harvesting factors assumed to interact during logging operations to influence fuel use have also been presented in this review. These factors include, but are not limited to, harvesting site topography (terrain factors), stand factors, equipment factors and ergonomic or human factors. Information on fuel consumption by harvesting systems and machines from selected published case studies has been presented. Existing logging costing models have been reviewed with respect to their approaches to fuel use estimation during costing for the purposes of economic viability and accountability. The review further provides a brief insight on forestry logging operations and emissions released to the environment upon use of fossil fuels. Finally, a summary of this review has been presented alongside presenting existing gaps identified in published fuel use studies specifically for the New Zealand scenario.

2.1 Fuel use estimation methods and units

2.1.1 Estimations of fuel use

Acquiring appropriate fuel use data is difficult and challenging due to the differences in the ways it is monitored and lack of mechanisms for recording fuel consumption data (Athanassiadis, Lidestav, & Nordfjell, 2002). Estimates of rates of fuel use by machine is more difficult if the available crew data is for a group of harvesting machines, and involves mixed harvesting systems such as cable yarding and two-staging with GB systems on a single setting (Athanassiadis et al., 1999). It has also been observed that records of fuel use by machines are difficult to obtain due to inappropriate and inaccurate approaches to recording and monitoring systems, given complex logging terrain and working conditions (Holzleitner et al., 2011). Research on fuel consumption rates for southern timber harvesting equipment established that only 60% of logging contactors keep records of fuel use (Greene et al., 2014), making it difficult to develop a proper benchmark for fuel use rates. However, in establishing the factors affecting fuel consumption and harvesting costs, Smidt and Gallagher (2013) observed that most logging contractors use the common rules of thumb to assign fuel use rates for machines, further casting doubts on record keeping on fuel use. They observed that most productivity studies aim at different objectives without specific approach to determining the variability in rates of fuel use and operational costs.

Logging under varying slope, directions of skidding and surface soil moisture conditions experienced by different crews indicate that fuel consumption rates tend to be highly variable (Nordfjell et al., 2003). This scenario leads to some key questions: (a) Do we measure the quantity of fuel used during timber harvesting? (b) How can we best collect information on fuel use to better our understanding on how it is used by machines and chosen harvest system? (c) Can an improved understanding of fuel use better our decision making approach?

Estimates of fuel consumption also vary due to differences in methods used for data collection. According to Acuna et al. (2012), methods of fuel estimation can take the form of a continuous data entry by on-board flow meter, shift level estimation through manual data entry from meter readings, tallying daily or weekly fuel data from pump meter readings, and/or acquiring the information from accounting data retrieved from fuel issued to machines by contracted fuel suppliers. Any of these approaches require adequate training of machine operators and proper exposure to the importance and accountability of fuel use for decision making and planning purposes (Pokorny & Steinbrenner, 2005; Spinelli & Magagnotti, 2011).

The accuracy of fuel consumption estimations is dependent on manual or automatic data entry systems (Spinelli et al., 2012). Given differences to the ways in which fuel consumptions is monitored and collected, variability in rates of use may be partly attributed to inappropriate methods of estimation and dependent on operators or individuals charged with the responsibility of fuel use monitoring and recording. Time studies have been used to estimate fuel consumption by logging machines through monitoring changes in depth of fuel tanks over a given productive time using a dipstick (Sherar & Dykstra, 1978). Sherar and Dykstra (1978), further suggested the use of brake-horsepower curves in developing a model for estimating fuel consumption rates for various cable rigging systems. However, estimations based on brake-horsepower curves and operation manuals (supplied by the manufacturers) only act as indicators of expected rates of fuel use by machines in an ideal logging environment (Klvac & Skoupy, 2009).

2.1.2 Units of fuel consumptions

Several publications on logging fuel use and productivity have reported average fuel consumption rates using units of measure which are sometimes completely different. For example, in analysing productivity and costs of mechanised cut-to-length wood harvesting system in clear-felling, Jiroušek et al. (2007) reported average fuel consumption in l/SMH for different classes of harvesters. A study on the utilization rates and cost factors in timber harvesting, based on long term machine data by Holzleitner et al. (2011), used both l/SMH and l/kWhr to report the average fuel consumption by harvesters and forwarders, respectively. Athanassiadis et al. (1999), reported rates of fuel use in litres per unit of production (i.e. l/m^3) for single grip harvesters when determining fuel, hydraulic oil and lubricant consumptions in Swedish mechanised harvesting operations. Similarly, Klvac and Skoupy (2009), expressed fuel use rates per unit of production (i.e. l/m^3) when reporting the results of the characteristic fuel consumption and exhaust emissions in fully mechanised logging operations. In New Zealand, Gordon and Foran (1980), reported rates of fuel use for yarders and wheeled skidders relative to machine weight in tonnes, and also fuel consumption by the same machines in litres per hour. Annual machine publication data by INFOMRE consulting in New Zealand has fuel use by various machines reported in l/SMH (FORME, 2012).

Given the similarity in machines studied by these authors, reporting average rates of fuel consumption using different units renders economic comparison, evaluation, and operational efficiency of similar machines difficult, due to differences in common denominator. Therefore, using unit of production (m^3) as a common denominator and relative measure for fuel consumption provides logging contractors with the opportunity to compare similar machines and harvesting systems in terms of operational costs, and also allows them to perform sensitivity analyses using different fuel prices to optimise their harvesting operations.

2.2 Harvesting systems and factors affecting fuel consumption

2.2.1 Harvesting systems and fuel consumption

Harvesting systems have been described and defined in different ways, and are the total sum of machines, equipment and people in relation to harvesting activities involving felling, primary transport, log processing, and loading (Kellogg et al., 1993). A harvesting system involves the interrelation of all the harvesting activities by machines, equipment, and available labour, all aimed at producing merchantable grade logs (Silversides & Sundberg, 1989). Harvesting systems have also been defined based on the method of primary transport (extraction), as ground-based (GB) or cable yarding (CY) systems (Visser, 2007). These definitions of harvesting systems are consistent to the logging terms defined by Stokes, Ashmore, Rawlins, and Sirois (1989).

Harvesting systems vary with type and can be motor-manual or mechanised (Karalus, 2010), thereby suggesting that average fuel consumption rates may vary considerably due to differences in modes of machine operation. A fully mechanised harvesting system involving a forwarder for extraction may be viewed as cost effective and energy efficient compared to skidding at longer distances, because of higher forwarder payloads (Jiroušek et al., 2007). Ground-based or cable yarding harvesting systems can handle harvesting products in the form of full or whole tree method (FTM or WTM), tree length method (TLM), cut-to-length (CTL), and chipping method (CM) done on clear-cutting/felling or thinning operations, as defined by Kellogg et al. (1993) (Table1). These harvesting systems and methods, due to variations in end products handled, require and are assumed to use fuel at different rates.

Table 1: Common harvesting methods (Kellogg et al., 1993)

Method	Description
Full tree method/whole tree method (FTM/WTM)	Whole tree felling and extraction to a landing or roadside with all branches and tops still attached to the stem.
Tree length method (TLM)	Felling, delimbing, and topping to various log lengths of standard small end diameters (SEDs).
Cut-to-length method (CTL)	Felling, delimbing, topping, bucking or crosscutting in log lengths ranging between 3-8m, and 4-6m.
Chipping method (CM)	Chipping or grinding at felling site.

Fuel consumption by GB and CY harvesting systems in New Zealand

Few logging fuel use studies have been conducted in New Zealand despite its production forestry ranking high on the global scale. Results of previous fuel use studies in New Zealand are accessible to only logging contractors affiliated with Future Forests Research (FFR), formerly known as Logging Industry Research Organisation (LIRO). Manual CY system is reported to use an average of 2.26 l/m³ (Sandilands, Nebel, Hodgson, & Hall, 2009), 2.76 l/m³ (Karalus, 2010), or 2.66 l/m³ (Dash & Marshall, 2011) for harvesting and handling a unit volume of timber. A fully mechanised CY system has been observed to use between 2.47 l/m³ (Sandilands et al., 2009) and 3.01 l/m³ (Karalus, 2010) during harvesting under New Zealand specific conditions. In another study, fuel consumption by CY systems are reported to range between 2.21 l /m³ and 6.09 l/m³ during logging, translating to an average consumption of 3.44 l/m³ for unit volume of timber produced (Dash & Marshall, 2011).

Fuel consumed during logging by a GB system under New Zealand harvesting varies per unit volume of timber produced and whether the operation is manual or mechanised. For example, Sandilands et al. (2009) reported a manual GB system to use an average quantity of fuel used for producing a unit volume of timber to be 1.96 litres/m³, compared to 1.98 litres/m³ reported by (Dash & Marshall, 2011; Karalus, 2010). The mechanised ground-based system is also reported to use fuel at an average rate of between 2.16l/m³ (Sandilands et al., 2009) and 2.76 l/m³ (Karalus, 2010). These fuel consumption rates by CY and GB harvesting systems have been conducted under assumed similar harvesting conditions in New Zealand. However, harvesting sites have differing terrain and stand variables, and crews skills vary with different work guidelines and logging management approaches (Spinelli et al., 2002) which all contribute to variability in rates of fuel use.

Notably, the rates of fuel use reported in these studies in New Zealand came from studies that were originally designed to investigate independent aspects of logging in relation to climate and supply chain other than logging fuel consumption. For example, studies by Sandilands et al. (2009) only estimated rates of fuel use based on data collected to quantify green-house gas emissions from forestry logging. Similarly, studies by Karalus (2010) reported rates of fuel use from an independent data set used in studying management supply chain emission. Of the three studies reported, the only independent study on logging fuel was conducted by Dash and Marshall (2011), who collected data from FFR members to establish the effects of future fuel costs on logging. Limited results and narrow scopes of these studies present a clear indication that little has been investigated on logging fuel use in New Zealand over the years and therefore justify further research on logging fuel use.

Case studies on logging fuel use

Fuel use studies by Smidt and Gallagher (2013)

In an effort to establish fuel consumption and harvesting costs for machines and harvesting systems variability, Smidt and Gallagher (2013) obtained data through a literature survey ranging from the last half of the 1970's to the time when their study was being conducted (2013) from published production studies. They reported fuel consumption by clearcut (CC) and thinning (THN) operations for ground-based crews working on southern yellow pine (SYP). In their results, they observed high variability in average rates of fuel use between skidders, which they attributed to differences in piece size handled and payload capacity. The study presented fuel consumption estimates for various whole tree harvesting systems and noted that variability between them was due to differences in type of cut, number of machines used, and whether processing was part of the harvesting activity (Table 2), but their analysis needed more data for statistical justification. Thinning systems were also observed to use more fuel compared to clear-cut systems, with inclusion of additional machines such as a delimber, resulting in increased rates of fuel consumption in the log length systems (LL). Their study indicated that most GB logging operations in the Southern US use three machines on average in any single harvest site at an average fuel use rate of 2.12 l/m^3 for every cubic unit of wood delivered to the mill. They concluded that most loggers do not document fuel use, making it difficult to understand the drivers of variability in rates of fuel use.

Table 2: Fuel use rates by harvesting systems adapted from Smidt and Gallagher (2013)

Harvesting system	Machines used	Fuel use rates (l/m^3)
Cut-to-length (Thinning)	FB & GSK	2.30
Cut-to-length (Clear-cutting)	FB & GSK	1.80
Clear-cutting (Log-length)	FB, GSK,LD & PRC	2.15
Clear-cutting - Thinning (Log-length)	FB, GSK,LD & PRC	2.75
Clear-cutting (Tree-length)	FB, GSK & LD	1.80
Thinning (Tree-length)	FB, GSK & LD	1.90
System average rates (Thinning)	***Three machines***	***2.32***
System average rates (Clear-cutting)	***Three machines***	***1.92***

**FB (Feller-buncher), GSK (Grapple skidder), LD (Loader), PRC (Processor)*

Fuel use by ground-based harvesting systems in Canada (Sambo, 2002)

In a study aimed at estimating fuel consumption rates by phase of harvesting and in total, from an entire GB harvesting operations in Western Canada, Sambo (2002) reported fuel use rates in litres of diesel equivalent per unit of production (l.d.e./m^3). The energy consumption during GB operations was recorded in mega-joules (MJ) of energy per unit volume of harvesting production (MJ/m^3) (Table 3). In the study, full-tree (FT) and cut-to-length (CTL) thinning operations used energy at the same rate per unit volume of wood harvested and delivered to the mill. The study also noted that energy consumption rates in cut-to-length operations at the stump site by harvesters and forwarders were lower by 17% and 19%, respectively, compared to full-tree systems. However, the author noted that conducting fuel use studies to obtain accurate rates of fuel used during logging was difficult since data acquisition from logging contractors was elusive and required trust and close relations.

Table 3: Rates of fuel use by ground-based harvesting systems in Canada (Sambo, 2002)

	Energy consumption in litres of diesel equivalent (l.d.e/m^3)*			
Harvesting system	**Felling**	**Skidding**	**Processing**	**System total**
Full-Tree (Clear-cutting)	0.75	0.62	0.70	2.08
Cut-to-length (Clear-cutting)	1.25	0.65	_	1.90
Cut-to-length (Thinning)	1.33	0.70	_	2.03
Full-tree (Thinning)	1.79	0.78	0.70	3.28
System average (Clear-cutting)	***1.00***	***0.64***	***0.70***	***1.99***
System average (Thinning)	***1.56***	***0.74***	***0.70***	***2.66***

*For energy conversion: 1 litre of diesel = 38.45 MJ of energy.

2.2.2 Factors affecting logging fuel consumption

Factors affecting logging fuel consumption can broadly be grouped into four categories: topography or terrain factors; stand and tree factors; machine and equipment factors and work or ergonomic factors. Basic descriptions of these factors and how they individually affect or interact to influence rates of fuel use during timber harvesting are briefly described in the sections that follow.

Slope

Harvesting site slope is the inclination of the landscape relative to flat surface (Beaty, 1959). Slope in timber harvesting context helps to determine the steepness of a given forest landscape. The inclination of the landscape can be flat, downhill or uphill relative level ground. Site inclination in logging helps to interpret the upward or downward direction of pulling during extraction and nature of difficulty during logging operations.

There are two basic categories of slope, an easy or a difficult slope. Easy slope is categorised as typically flat site of 0-15% slope, while difficult terrain is considered to be greater than 70% slope (Sundberg & Silversides, 1988). Increased percent slope has been observed to result to additional weight being exerted on yarding or skidder loads and thus require horizontal adjustments on the ground to reduce resistances due to traction between the load and the ground (Tomašić, Šušnjar, Horvat, & Pandur, 2009). Such resistances are associated with additional rates of fuel use required to inject more power to the engines to overcome the effects associated with adverse gradients, to improve on machine efficiency. It has also been observed that fuel consumption rates vary with the type of harvesting system used by a crew due to variations in percent of slope of harvesting site (Karalus, 2010).

Soil moisture conditions

The type of soil at the harvesting site determines site drainage patterns. Poorly drained soils affect machine traction during harvesting operations. Sandy soils with wide pore spaces allow for faster drainage compared to clay and loam soils with relatively smaller grains and poor drainage that occasionally result to water logging or flooding of harvest sites. Soil surfaces can be considered dry, moist, and or wet depending on the level of drainage, soil moisture, and water balance. Changing weather seasons may result to variability in soil moisture resulting to dry, moist or wet harvesting conditions. Wet weather affects machine movement during felling and extraction as a result of loss of traction between the tyres and the ground. Loss of traction due to poor soil drainage creates potential for machines sliding or becoming stuck in muddy conditions resulting in safety issues as well as halting productivity. Additional force required by the machines to overcome the resistance due to loss of traction, necessitated by varying soil surface conditions, requires more fuel to overcome the resistance compared to quantities needed to perform normal primary functions of logging.

Direction of pulling during extraction

Extraction of logs or stems from stump sites to landings can be towards uphill or downhill directions for a steep or rolling slope site or towards any direction on flat slope,. Steep slope harvesting by CY system may result in high rates of fuel use when extraction is done on an uphill direction of pulling against the slope, as opposed to pulling downhill due to resistances by gravitational forces (Holzleitner et al., 2011). Skidders pulling in an uphill direction use fuel at higher rates (Makkonen, 2004) due to resistances associated with the effects of adverse gradient compared to low fuel use rates associated with machines loaded and moving downhill whose motions are aided by gravitational force due to favourable gradient. It has also been observed that resistances experienced by skidders when pulling in an uphill direction are characterised by increased engine torques and the effects of machine weight, relative to increased traction forces (Tomašić et al., 2009). Overcoming increased traction force requires more engine power that is only achievable at higher rates of fuel use.

Extraction distance

This is the distance from the point of felling (stump/tree growing) to point of processing, a roadside or landing. Extraction machines take longer to reach landings or roadsides which are far away from the point of felling. Longer extraction distances from landing or processing points, depending on slope and other factors require more fuel for mobility compared to machines on shorter extraction distances. However, no research has been done to establish how fuel consumption and extraction distances relate.

Stocking density and tree spacing

Stocking density influences machine productivity on a given harvesting setting in terms of net volumes of wood harvested. For example, it has been noted that forwarders produce more wood volumes at stands with higher net stocking per unit area at shorter extraction distances (Di Fulvio & Bergström, 2013). Harvesting sites with high stocking densities allow for faster accessibility of stems by machines during felling, due to closer tree spacing, and are more productive resulting in reduced rates of fuel use (Baker, Mei, Harris, & Greene, 2014). Larger spacing between trees translates to specialised felling machines, like feller-bunchers or harvesters, covering longer distances to access the next tree. Since machine productivity during harvesting operation is a time function (Tolan & Visser, 2015), machine productivity is lost, whereas fuel is consumed in the process. Additionally, larger harvesting areas require more time to harvest than woodlots, which results in greater fuel use by machines for operations conducted on expansive forests than comparable homogenous forests in woodlots.

Tree size (piece size)

Tree size in logging industry terms refers to the size of the stem being handled by machines during and after felling. It is the ratio of 'total volume per unit area of forest' to the number of established trees in a production forest; with the most commonly handled commercial log size referred to as piece size (Sundberg & Silversides, 1988). Processing productivity during harvesting increases exponentially with increase in piece size (Visser & Spinelli, 2012). However, there is no existing published literature to justify any relationship between tree size and the rates of fuel use by machines and harvesting systems during logging. It is perceived that harvesting larger piece sizes is associated with benefit of economics of scale due to reduced rates of fuel use. However, this economic benefit diminishes the moment a felling machine begins to struggle with larger tree sizes, as productivity gains at such a point do not breakeven (Visser & Spinelli, 2012). More productive time is also lost by the machine when handling a single piece size resulting in increased rates of fuel use.

Equipment factors

Machines are manufactured with different designs, technology, and transmission systems aimed at improved operational efficiency (Lindholm & Berg, 2005). Engine specifications vary in their level of in-built technology from one manufacturer to another (Spinelli & Magagnotti, 2011). Makkonen (2004), observed that for any quantity of fuel used, 60% is due to variability in equipment design, 20% associated with the level of engine technology, and the remaining 20% is accounted for by operators differences and level of operational experience. Harvesting machines are also categorised as off-road and vary with engines types and sizes (Athanassiadis, 2000; Jiroušek et al., 2007), indication that different machines use fuel at different rates during harvesting.

Rate of fuel consumption is noted to increase considerably when engines are operated at high speeds (Makkonen, 2004). Operator training on fuel saving techniques should therefore be considered as an integral work component in decision making. The realisation of fuel saving economics and operational efficiency, as acquired by fuel saving skills practiced by operators, makes operators an important component in fuel savings (Spinelli & Magagnotti, 2011). Furthermore, logging machines handle logs of various payloads and operate for variable PMH resulting in varying load factors during normal operations. This implies that individual machine fuel use is dependent on equipment load factors and work intensity (Capehart, 2000; Spinelli & Magagnotti, 2011).

Ergonomics/Human factors

Ergonomics in logging industry is the relationship between crews and equipment/machines in logging work environment (Silversides & Sundberg, 1989). Operator skills and competence, work attitude, body health, psychological orientation, body adjustment to forest microclimate conditions during work and understanding of the work environment all form an integral part of meaningful productivity output. These factors do not act in isolation but rather interact to affect the operator performance, resulting in varied productivity outputs. Therefore, operators charged with the responsibility of balancing between fuel use documentation and machine operation under such psychological orientation may resort to approximation, thereby lowering the resolution of documented data due to inaccuracies in recordings. Inaccuracies associated with withdrawal work psyche also hinder the realisation of economic viability and operational efficiency of a logging operation. Fuel consumption by harvesting systems and machines has been observed to be influenced by the interaction of terrain, stand, equipment factors and ergonomics under complex work environment (Makkonen, 2004; Spinelli & Magagnotti, 2012). It has been established that no single factor in logging environment acts in isolation to affect fuel consumption rates, but it is rather the total interaction of all the factors (Holzleitner et al., 2011; Jiroušek et al., 2007).

2.3 Logging machinery and mechanisation

2.3.1 Logging machinery and fuel consumption

The discovery of coal in the 13th century led to the development of steam engines, locomotives, steamship and steam electric power engines (Hubbert, 1949). This was followed by the discovery of petroleum and natural gas later in the 19th century that led to further development of internal combustion engines, automobiles, and diesel electric power transmission systems and further development and improvement of engines (Hubbert, 1949). Athanassiadis, Lidestav, and Wästerlund (2000), noted that a rise in diesel engine technology was informed by readily available diesel oil, providing a cheaper form of fuel compared to petrol. Logging machines are designed with diesel engines to work under forest conditions and built with combinations of movable parts, operated motor-manually or mechanically, by using less effort and energy compared to physical human labour. The most commonly used logging machines have been defined and described based on their primary function(s) by Kellogg et al. (1993).

Theoretically, engine fuel system is comprised of a fuel tank, strainer, pump, filter, pipes, injector and flow control valves (Sessions, 2007). When the engine is set in motion through ignition by a machine operator, fuel is pumped and flows from the tank through the strainer, filter, and cylinder head. Fuel is then sprayed into the combustion chamber where it is ignited and combusted due to the injected compression air pressure and ignition spark. The pressure generated in the combustion chamber initiates power transmission to the shaft connecting the sprocket to the wheel. The compression heat generated in the combustion chamber is then transferred through a torque converter to generate twisting force. This twisting force is increased by torque multiplier through injection of more fuel into the combustion chamber and then delivered to the sprocket, wheel, and drums along the power train (Sessions, 2007) (Figure 2). During power shift, fuel consumed by machines is dependent on power rating (Brinker, Miller, Stokes, & Lanford, 1989), mode of transmission and machine load factor (Edwards, Larivé, Mahieu, & Rouveirolles, 2006).

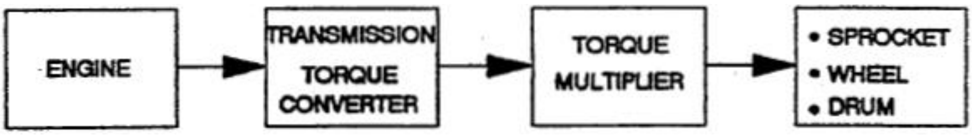

Figure 2: Power transmission in engines (Sessions, 2007)

Machine work elements and fuel consumption

Work elements for various harvesting machines differ with felling, extraction, processing and loading operations (Spinelli & Magagnotti, 2012). Table 4 shows some various work elements associated with fuel consumption and specific to machines used and harvesting phases.

Table 4: Primary machine functions and work elements associated with fuel use during logging

Operational function	Various machine work elements
Felling	Clearing felling area/escape routes, opening cut, back-cut, delimbing, topping, and crosscutting.
Felling and bunching	Driving to felling site, swinging to/tree grabbing, directional cutting/felling, and bunching.
Felling & Processing	Driving to felling site, swinging to stem or tree, severing/cutting, delimbing, topping, bucking and sorting.
Forwarding	Travel empty to stump site, grabbing, loading, travel back to landing loaded, offloading, pilling to log grades.
Skidding	Travel empty from landing to stump site, hooking of logs, travel back loaded to landing, unload or unhook.
Cable yarding	Outhaul (carriage travel empty), Hook stems/chocker setter, Inhaul (travel back loaded by carriage), and Unhook/offload stems on landing.
Processing	Driving to stem or log deck, grabbing the stem, delimbing/topping/bucking, and sorting into grade piles.
Loading & Storage	Travel empty to processed piles/log grades, hook logs, travel loaded to sorting/storage piles, off-loading at grading/sorting area, and loading of trucks.

The evolution of logging machinery over time has been influenced by advancements in technology and rapid mechanisation with different types, make, engine designs and fuel tank capacities (Kellogg et al., 1993). The quantity of fuel consumed by individual logging machine has been reported as dependent on slope, soil moisture conditions, operator work habits and skills, and level of mechanisation (Klvac, Shane, Omende, & Loyns, 2003; Makkonen, 2004; Sandilands et al., 2009; Spinelli et al., 2011; Spinelli et al., 2002; Stampfer, Visser, & Spinelli, 2009). Rates of fuel use has also been reported as dependent on a machine's weight, engine power rating, and mode of power transmission (Jiroušek et al., 2007). Since energy use is dependent on individual machine work elements, different machines are therefore assumed to consume different quantities of fuel, even under similar work environment. Since different logging crews select and use different numbers and types of machines based on the uniqueness of harvesting sites (Ghaffariyan & Brown, 2013), information on rates of fuel use should be used to guide such selection.

Felling machines

New machines come with indicative fuel consumption rates detailed in operation manuals for ideal logging environments. However, there is no 'ideal logging environment' when considering the variability between most production forests in terms of stand, terrain charateristics, and differences in landscapes of establishemnt. For example, fuel consumption by a motor-manual chainsaw has been reported to be greater than the rates indicated in chainsaw operation manuals by the manufacturers (Gordon & Foran, 1980). Gordon and Foran (1980), also reported that ideal working environment for chainsaws is not practical, since chainsaws are used for felling different tree species with distinct density variations, and operated by people with varied expertise and machine handling skills. However, motor-manual chainsaws still dominate steep terrain felling despite the fact that alternatives could be used in areas without steep terrain, and constitute 77% of most felling in New Zealand (Visser, 2011), and are good at addressing variability in forest settings as opposed to harvester and/or feller-buncher machines (Spinelli et al., 2002).

Specialised and mechanised steep terrain felling machines, such as feller-bunchers and harvesters, are heavier compared to motor-manual chainsaws, and fitted with large engines that on average use more fuel during logging than chainsaws (Jiroušek et al., 2007). Average fuel consumption relative to SMH by these specialised felling machines varies with power rating and engine sizes. For example, small feller-buncher rated 80 kW consumes 10.9 l/SMH, while harvester rated 120 kW consumes 12.8 l/SMH (Jiroušek et al., 2007). Similarly, a medium-sized harvester rated between 80 kW and 120 kW consumes 15.4 l/SMH (Athanassiadis et al., 1999) while in general, a harvester is reported to consume 0.09 l/kWhr (Holzleitner et al., 2011). Rates of fuel consumption per unit of production by harvesters has been reported by Klvac and Skoupy (2009) as anywhere between 1.28 l/m^3 and 1.73 l/m^3. Athanassiadis et al. (1999), also studied and reported rates of fuel use by single-tree grip harvesters as 1.17 l/m^3 of wood under bark.

Harvesters and forwarders studied and reported by Athanassiadis et al. (1999), Jiroušek et al. (2007), Klvac and Skoupy (2009), and Holzleitner et al. (2011), are however, smaller in terms of size and weight compared to modified felling and processing machines used in New Zealand. For example, a processor consisting of processing head attached to an excavator machine consumes up to 40 l/SMH according to machine data by FORME (2012). Since felling operations are difficult to perform with harvester machines due to dangers of increased instability posed by steep slopes (Spinelli et al., 2009), additional machine such as a bulldozer may be used for anchorage in tethered felling operations (Visser, 2013). More fuel is thus needed for the additional anchorage machine and this translates to increased fuel supplies and, by extension, more average fuel consumption by harvesting systems relative to unit volume of harvesting production.

Extraction machines

Primary transport involves use of skidders, cable yarders and forwarders. Is has been reported that tower yarders use an average of 0.06 l/kWhr, skidders 0.08 l/kWhr, and forwarders 0.10 l/kWhr (Holzleitner et al., 2011). However, evaluating the economic efficiency of different extraction methods and machines is difficult since it is not easy to assign value to the power rating of an individual machine. A cable yarder rated between 185 kW and 225 kW consumes 20 l/SMH for every 20 tonnes of timber hauled to a landing, while a yarder rated between 300 kW and 355 kW is reported to consume 39 l/SMH for hauling 27 tonnes (Gordon & Foran, 1980). Comparing yarder fuel consumption between studies conducted by Gordon and Foran (1980), to those done by Holzleitner et al. (2011), is impossible due to differences in the common denominators used relative to fuel consumed. Gordon and Foran (1980), further reported that a wheeled skidder rated between 110 kW and 150 kW consumes fuel at the rate of 15 litres for skidding 40 tonnes of timber to a landing per SMH.

Nordfjell et al. (2003) reported average fuel consumption for forwarder studies ranging between 0.28 l/m^3 and 0.36 l/m^3 of timber moved for an average extraction distance of between 458 m and 514 m respectively. Such results are important to regions with full logging mechanisation specifically for mechanised cut-to-length systems where most forwarders are much needed, since they are economical at longer extraction distances. In separate studies, Holzleitner et al. (2011), noted that a forwarder consumes fuel at the rate of 10.9 l/SMH, while Klvac and Skoupy (2009) when establishing the characteristic fuel consumption and exhaust emissions in fully mechanised logging operations, observed that forwarders use between 0.75 l/m^3 and 1.36 l/m^3. Klvac and Skoupy (2009), further observed that a forwarder rated 152 kW consumes fuel at an average rate of 15 l/SMH while that of 138 kW consumes 12.5 l/SMH. Athanassiadis et al. (1999), also found that forwarders consume fuel at the rate of 0.94 l/m^3 of wood under bark. These studies sought to determine rates of fuel use by forwarders, however, denominators of different units renders economic comparison between such machines and similar ones from other fuel use studies results difficult.

Other machines

Mechanised processing has increased from 40% in 2011 to 48% in 2013, an indication to the rise in use of more specialised harvesting and processing machines (Visser, 2013). Front-end loaders use fuel at an average rate of 16 l/SMH while knuckle-boom loaders use fuel at the rates of 32 l/SMH (FORME, 2012). In establishing net energy output from harvesting small-diameter trees using a mechanised system, a front end loader was observed to consume diesel fuel at lower rates compared to a skidder of similar power rating (Pan, Han, Johnson, & Elliot, 2008). Spinelli and Magagnotti (2011), observed that if chipping is part of harvesting productivity, then there is the risk of increased total harvesting costs due to energy consumption associated with additional chipping machines, since chippers are reported to use 0.5 l/m^3 of chipped wood, (Spinelli et al., 2012). A summary of rates of fuel use by different authors compared has been presented in Table 32 under results section.

Case studies on logging fuel consumption by machines

In Canada, Makkonen (2004) under Forest Product Innovations (FPInnovations) conducted fuel use studies to establish the possibility of fuel savings for logging machines. According to (Makkonen, 2004), since the average rates of fuel consumed by different machines varies considerably (Table 5), fuel conservation strategies are needed to reduce harvesting costs.

Table 5: Hourly fuel consumption rates by Canadian logging machines (Makkonen, 2004)

	Fuel consumption (l/hr)	
Machine	**Range**	**Average**
Feller-buncher	30 – 40	35
Tracked single grip harvester	14 – 25	19.5
Wheeled single grip harvester	10 – 19	14.5
Delimber	21 – 26	23.5
Grapple skidder	20 – 30	25
Large clambunk skidder	32 – 44	38
Small forwarder	06 – 10	8
Large forwarder	10 – 16	13

In another perspective, using data obtained from the Austrian Federal Forestry company, Holzleitner et al. (2011) analysed the importance of long term machine data on harvesters, skidders, forwarders and tower yarders to validate machine costing schedules using, among other components, fuel consumption based on machine utilisation rates. Results of this study show that average fuel consumption per productive machine hours (PMH) for harvesters ranges from 10.2 to 24.3 l/PMH, with forwarders using an average rate of 11.1 l/PMH, tower yarders 16.0 l/PMH and skidders at 7.3 l/PMH. The results also show that tower yarders consume fuel at the lowest average rates per unit of power drawn compared to harvesters, forwarders and skidders (Table 6). Holzleitner et al. (2011), developed a model for determining fuel consumption rates for different machines as a function of power rating by type of machine used.

Table 6: Rates of fuel consumption in l/PMH and l/kWhr (Holzleitner et al., 2011)

Machine type	Power (kW)	Average power (kW)	Fuel consumption	
			l/PMH	l/kWhr
Harvester	125-204	165	15.6	0.09
Forwarder	82-150	116	11.1	0.1
Skidder	75-150	113	7.3	0.08
Tower yarder	170-330	250	16	0.06

In a survey aimed at determining fuel consumption rates of mechanised timber harvesting equipment, Greene et al. (2014) obtained machine data for thinning and clearcut operations using fuel meters and in-built machine data recording systems between November 2012 and April 2014 in southeast Georgia, USA. Results showed that feller-bunchers and grapple skidders use fuel at the same rate per unit of production compared to stationary knuckle-boom loaders. Variations in average fuel consumption rates between feller-buncher and grapple skidders was attributed to differences in transmission systems, as grapple skidders used power-shift transmission compared to hydrostatic transmission system for feller-bunchers. Variation in average fuel consumption rates for grapple skidders was also attributed to differences in extraction distances and maximum allowable payloads. The study concluded that for a mechanised GB harvesting system involving feller-bunhers, grapple skidders and knuckle-boom loaders, average system fuel consumption was 1.58 l/m^3 (0.38gallon/ton) ranging from 0.85 to 1.70 l/m^3 (0.25 to 0.50 gallon/ton). These rates of fuel use constitute between 15 to 20% of total harvesting and secondary haul costs, and are subject to variation with changing fuel prices. However, a relationship could not be analysed or determined between these average consumption rates and harvest site factors such as slope, extraction distances and surface conditions as the available data used in the study did not capture these harvesting attributes to verify their effects on fuel consumption rates.

In Sweden, hydraulic oil and lubricant consumptions by harvesters and forwarders in mechanised harvesting operations have been studied through a random survey using a logging business register provided by statistics Sweden (Athanassiadis et al., 1999). For purposes of their data analysis, Athanassiadis et al. (1999) grouped harvesters and forwarders into three classes based on maximum payloads and power rating: small-sized, medium-sized and large-sized. Results showed that large-sized harvesters and forwarders with a higher power rating consume less fuel per unit of production on average, compared to medium and small-sized harvesters and forwarders of low power rating, respectively (Table 7). The results of this study suggest that smaller machines engaged for high production beyond their productive limits suffer reduced productivity due to mechanical struggle when design limits are exceeded. As has been observed by Visser (2009), and Visser and Spinelli (2012). Variability on average rates of fuel consumption by respective machines in this study was also attributed to differences in payloads and rated power. Moreover, the authors suggested that average fuel consumption was dependent on harvesting system used, phase of harvesting, end product, stand and terrain factors, machine attributes, and machine operator. The results of this study further provided a platform for life cycle analysis of harvesting machines based on fuel, hydraulic oil and lubricant consumption.

Table 7: Rates of fuel consumption by Swedish felling machines (Athanassiadis et al., 1999)

Machines	Class	Weight	Power (kW)	Fuel consumption (l/m^3)
Harvester	I	10 tons		1.22
	II	10 – 12 tons		0.90
	III	>12 tons		0.88
Forwarder	I		80 kW	1.85
	II		80 – 120 kW	1.22
	III		>120 kW	0.96
Two – grip Harvester	-		-	1.01

2.3.2 Mechanisation and fuel consumption

Large scale mechanised logging operations have been observed to use higher rates of energy (fuel equivalent) per unit volume of production compared to motor-manual operations on similar scales (Lindholm & Berg, 2005). Lindholm and Berg (2005) also noted that variations in rates of energy use has been on the decline with a shift towards full logging mechanisation and new development of efficient engines. Harvesting crews in New Zealand use either mechanised, manual, or a combination of both operations interchangeably, based on slope characteristics of the harvesting site and method of felling (Karalus, 2010; Sandilands et al., 2009; Visser, 2011). Average rates of fuel use by various types of harvesting systems relative to levels of mechanisation have also been reported in New Zealand by Sandilands et al. (2009), Karalus (2010), and Amishev (2010). Results on rates of fuel use from these studies have been reviewed and compared with findings from research conducted to determine the effect of future fuel costs on harvesting costs in New Zealand by Dash and Marshall (2011).

Comparatively, the level of logging mechanisation differs significantly from one country to another, with fully mechanised cut-to-length systems accounting for up to 98% of harvesting operations in Sweden, 95% in Ireland and 95% in Finland (Klvac & Skoupy, 2009). Currently in New Zealand, there is a general shift towards full mechanisation of logging operations due to increased concerns for worker safety (Visser et al., 2014). Since logging mechanisation comes with new technology and engine design sophistication (Lindholm & Berg, 2005), machine operators need to be fully equipped with advanced operational skills through training on new machine features in terms of energy consumption rates and productivity for purposes of being fuel saving conscious to facilitating operational efficiency.

Fuel consumption has also been observed to vary between mechanised and manual harvesting systems due to machines involved, and researchers have suggested use of harwarder, a combined harvester and forwarder machine, for purposes of fuel economy (Lindholm & Berg, 2005). However, mechanisation for fuel conservation can be applied depending on the type of machine and the logging operation involved. For example, a forwarder is a fully mechanised logging equipment that has been reported to consume between 8.3 l/SMH and 15.7 l/SMH by combining both felling and processing when harvesting mainly smaller trees (Jiroušek et al., 2007). However, absence of forwarders in most logging operations in New Zealand could be associated with low productivity and loss of advantages of economies of scale associated with high harvesting production. Moreover, latest improvements and rise in development of engine technology have been aimed at increased operational efficiency in logging as observed by Athanassiadis (2000), making loggers in Sweden, Finland, and Canada adapt to fully automated and mechanised harvesting systems with low fuel consumptions.

2.4 Logging productivity and operational efficiency

2.4.1 Logging productivity and fuel consumption

Forestry harvesting operations are aimed at value recovery from production forests (Tolan & Visser, 2015). Being more productive and fuel efficient for a given harvesting system and selected machines allows for optimisation of operational costs. Logging managers are driven by set production targets that are timely delivered to the customer for maximum returns and operational sustainability (Pokorny & Steinbrenner, 2005). Production volumes delivered to the customers and mills are frequently used by most logging crews as performance indicators of operational efficiency (Drolet & Lebel, 2010). However, since production volumes are time functions (Smidt, Tufts, & Gallagher, 2009), engaging machines on non-productive work results to use of more fuel without justified productivity outputs. This leads to loss of fuel economy as production volumes lost during non-productive operations by machines translate to increased operational costs related to fuel consumption. Consequently, production forests in harvesting planning by most logging contactors are generally viewed as infinite (Sundberg & Silversides, 1988). Therefore, exploitive approaches have been adopted by most logging crews including longer schedule machine time to maximise on harvest volumes. Focusing more on production volumes by engaging machines for longer productive time leads to increased use of fuel and daily operational costs (Pokorny & Steinbrenner, 2005). Furthermore, high production volumes require proper fuel supply planning based known consumption trends by machines and harvesting systems towards achieving technical efficiency and economic viability (Sundberg & Silversides, 1988).

Engaging machines, such as a skidder, for longer productive time on low productive forest sites has been noted to increase rates of fuel use due to low production output (Ghaffariyan & Brown, 2013), thereby inflating total harvesting costs (Spinelli et al., 2009). Operational delays and machine interactions during productive time have been noted to be complex and not easy to understand (Visser, 2013), as more fuel is consumed on non-productive time and machine movement.

2.4.2 Operational efficiency and fuel consumption

Operational efficiency in logging has been defined as the ratio of production achieved by machine based on actual productive machine time relative to scheduled operational time (Smidt et al., 2009). A harvesting system can be considered efficient and cost effective (Visser, 2007), if it achieves the objective of producing wood volumes for sale at a minimum input of resources available (Hackman, 2008). Efficiency and effectiveness of a given logging system and its economic viability can also be assessed in terms of fuel consumption rates in litres per unit of production, and response of these rates of use to harvesting costs with changes in fuel prices.

Optimised harvesting planning under the guidance of well understood fuel use is imperative for economic viability and efficiency in a competitive log market given the dynamics in fuel supply and pump prices (Hackman, 2008). However, reliance on operational efficiency based on rates of fuel use is limited to country and region of data collection (Ghaffariyan & Brown, 2013; Pierre et al., 2014). Use of benchmarks on rates of fuel use developed in other regions is also limited by inadequate understanding of harvesting site factors and their interactions in determining rates of fuel use in the region of model development. Fuel reduction strategies have been suggested towards achieving operational efficiency in logging with machines that are fossil fuel reliant (Makkonen, 2004; Sundberg & Silversides, 1988).

2.5 Emissions associated with logging fuel consumption

In forestry operations involving planting, silvicultural activities, logging and secondary log transport, machines used at every stage combust fossil fuel and release exhaust gases into the surrounding environment (Athanassiadis, 2000; Klvač, Fischer, & Skoupý, 2012; Klvac & Skoupy, 2009; Sonne, 2006). Of all these forestry activities, timber harvesting operations have been reported as the biggest emitter of greenhouse gases into the environment (Athanassiadis, 2000). Estimates of actual quantities of fuel consumed by machines during logging can be used to quantify the amount of greenhouse emission into the environment through mathematical algorithms (Berg & Lindholm, 2005).

Records of logging fuel use are also important in determining life cycle analysis (LCA) of harvesting machines (Berg & Lindholm, 2005). Forest growing companies can rely on fuel use information from logging contractors to audit the quantities greenhouse gas emissions in the event that their forest stands are harvested, to ensure compliance with international climate change conventions of countries of emission. Individual quantities of CO_2 and noxious gases released during fuel combustion in the engine can equally be determined given the availability of logging fuel consumption data (Athanassiadis, 2000). It is estimated that 9.63 kg/m^3 of CO_2 is emitted into the environment when diesel is combusted during mechanised harvesting operations (Klvac & Skoupy, 2009). Studies in Sweden by Athanassiadis (2000) further show that about 1% of CO_2 and 1.6% of noxious gases are released by harvesters and skidders into the environment. However, few studies have been conducted to establish the actual quantities of fuel used during logging to facilitate determination of greenhouse emissions into the environment (Athanassiadis et al., 2002).

2.6 Logging costing models and determination of rates of fuel use

Several logging costing models have been used to calculate machine rates and unit harvesting costs by providing estimates of fuel use rates for machines fitted with diesel engines. Logging industry Research Organisation (LIRO) developed a costing spreadsheet schedule for machine rate calculations and determination of unit harvesting costs in New Zealand, and this was updated in the new Business Management of Logging handbook (Alastair, 1994). The model specifies rates of fuel use for ground-based operations as 0.16 l/kWhr and 0.11 l/kWhr for cable yarding operations, and was developed using older machine models of the 1980s. LIRO model however, only specifies rates of fuel use by type of logging operation; it does not provide an adjustment factor for varying rates of fuel use due to the effects of terrain and stand variables that impact on harvesting costs.

In determining fixed and operating costs of logging equipment, Miyata (1980) provides benchmark estimates of rates of fuel use for machines with diesel engines as 0.037 gal/hp-hr or 0.14 l/kWhr. The Miyata (1980) model however, does not specify nor categorise various logging machines used during operations as either GB or CY, as is the case of LIRO model. Therefore, the Miyata (1980) model should be used as guideline for expected rates of fuel use during machine costing, but actual rates of fuel use should be determined using the prevailing harvest site factors of a given region. A logging machine rate analysis using a charge out model, developed by Bilek (2009a) and, adopted from the Miyata (1980) model, reports rates of fuel consumption for a given machine as 0.03 gal/hp-hr or 0.15 l/kWhr for an ideal logging environment. However, it does not account for the effects external harvesting site factors that can influence rates of fuel use by machines.

In rare cases, specific fuel use determination models for some machines have been developed. For example, fuel consumption by a bulldozer machine commonly used for skidding and as tailhold is taken as a product of hourly fuel consumption in gallons per horsepower as 0.3 gal/hp-hr (or 1.52 l/kWhr) and machine load factor (Runge, 1998). This model has been applied by Filas (2002) to determine rates of fuel use for excavation and loading machines. However, models developed by Runge (1998) and Filas (2002) are difficult to implement due to the difficulty in assigning machine load factors during operations. Load factor in this context, is the ratio of engine output power to the available engine rated power (Capehart, 2000). For example if a machine has its engine rated 250 kW and only gives 180 kW as an output when under normal work conditions, then the load factor is the ratio of the output to the rated power which is 72% in this case.

Determining load factor for various machines may be difficult, but a study on bulldozers has shown that reducing engine load factor by 15% leads to significant reduction on fuel consumption (Kecojevic & Komljenovic, 2011). Moreover, rates of fuel use determined based on Miyata (1980), Bilek (2009b) , Runge (1998), and Filas (2002) models are derived from the ratio of specific mass of diesel fuel burnt (when a diesel engine is operating at full throttle) to its specific density on an hourly basis, as presented in wells to wheels by Edwards et al. (2006). Fuel use rates have also been determined based on pump prices and productive machine hours (l/PMH) (Pierre et al., 2014). However, Pierre et al. (2014) cautioned that only accurate data provision can give correct fuel use estimates, and decried the decreasing number of logging contractors sharing their fuel use data with researchers.

In acknowledging that these logging costing models are important for assisting logging contractors and operational managers in apportioning rates of fuel use for costing purposes, they are limited to being country specific because of the data used in their developments, tax regimes, and existing logging legislations (Pierre et al., 2014). For example, the charge out model (Bilek, 2009b) and well to wheels analysis (Edwards et al., 2006) are both designed for use specifically in the USA. However, the Miyata (1980) model, because of use of standard rates for diesel engines based on hose power rating by machine, is easily applicable in any scenario irrespective of region for determination of fixed and variable logging costs.

Some logging cost models are also based on combined ratios dependent on machine power rating and load factors as opposed to production volumes harvested. Therefore assuming rates of fuel use based on a single attribute of power rating as the main driver of fuel use rates, for any given machine, may not reflect the actual fuel consumption subject to terrain and stand variability of any given logging site. Rates of fuel use in l/kWhr based on these models provide a robust means of fuel costs control. However, it does not give any economic indication relative to production volumes of logging operation. Therefore, it would be imperative to develop a benchmark on rates of fuel use based on wood volumes produced during logging, as production volumes can be assigned monetary values and used as a measure of efficiency between machines and harvesting.

Published machine fuel use data (FORME, 2012) in New Zealand

Machine data by FORME (2012) can be used to determine rates of fuel use by individual machine based on annual fuel costs, SMH and annual number of harvesting days. However, INFORME Consulting company in New Zealand (FORME, 2012), does not provide or have a benchmark for fuel use by logging systems and machines but only indicate annual possible fuel costs for various machines. Estimates of fuel costs by machines provided by FORME (2012) data are also based on machine calculations derived from operational manuals and data from random survey of logging contractors. In FORME (2012) machine data, harvesting conditions such as slope, directions of pulling and surface moisture during operations are assumed as standard variables irrespective of type of harvesting operation. However, ideal forests are highly unlikely in New Zealand according to Gordon and Foran (1980), as most logging contactors operate for more than 175 days a year reported in FORME (2012) data. Logging crews also keep moving to new harvesting sites with changing terrains and stands, which are recipes for variability in rates of fuel use during logging. Furthermore, FORME (2012) data does not allow for determination of rates of fuel use in l/m^3 as there is no production data by machines. Notably, FORME (2012) publication has the advantage of providing logging contactors with quick reference to annual productive machine hours, average cost of fuel, machine specification (power rating, type, weight) and total annual fuel consumption estimates (see Appendix 5). Such information is useful for machine rate calculations; however, real time data on production is needed to determine actual fuel consumption rates subject to prevailing harvest site variables.

2.7 Percentage of fuel costs in unit harvesting costs

Knowing the percentage of input costs associated with labour, capital, and fuel in total harvesting cost is important for harvesting planning as it helps to monitor the changes associated with variable costs over a given time (Baker & Greene, 2012; Bilek, 2009b; Dale Greene, Erick Biang, & Baker, 2014; Greene et al., 2014; Pierre et al., 2014). Labour costs and machines can be controlled for a given harvesting system, unlike fuel prices and inflation (Spinelli & Magagnotti, 2011). Fuel is a major variable input cost in logging accounting for 10 - 22% of total harvesting costs (Baker & Greene, 2012) and is attributed to volatility in fuel prices and variability in market log prices. The variations in the proportion of fuel consumption during logging are confirmed by Dale Greene et al. (2014) to be between 15 and 20% of fuel costs in total harvesting costs. Fuel costs are also reported to account for an average of 22.8% of the total harvesting costs in a study on index for logging cost, by Baker et al. (2014). These studies have been concentrated in the United States of America, and reflect how fuel consumption costs form significant component of input cost in timber harvesting. The percentage of fuel consumption in total logging costs for a GB or CY system in New Zealand is not easy to determine due to lack of available data. However, the proportion of fuel consumption costs for both harvesting systems are estimated in the range of 17 to 35% using rates of fuel use by Karalus (2010) and annual benchmarking data (Visser, 2013).

2.8 Fuel use research scenario in New Zealand

The need to obtain information on logging fuel use in New Zealand followed an energy crisis in the 1970s. Research began in 1980 when Gordon and Foran (1980), under the then Logging Industry Research Association (LIRA), reviewed fuel use in logging to help logging stakeholders understand fuel use for purposes of operational efficiency. The researchers obtained data on fuel use and production, from Kaingaroa Logging Company associated, with chainsaws, extraction machines (crawler tractors, wheeled skidders, and cable haulers), loaders, log trucks, and log stackers and determined rates of fuel consumption per unit of production. According to the results of the study, the actual fuel consumption rates by chainsaws were significantly higher than published consumption rates specified in operation manuals. Actual fuel consumption by loaders was also observed to be less than published rates and was attributed to shorter productive work cycles during loading as engines were switched off while awaiting incoming log trucks for more loading activities.

With data on engine sizes (kW) and slope characteristics of site, they determined average fuel consumption rates in litres per hour (l/hr) and in litres per unit of production (l/m^3) (Table 8). The results showed that cable haulers with large engines consumed more fuel on average compared to cable haulers with smaller engine sizes. Crawler tractors also used higher rates of fuel compared to skidders for similar operations under similar harvest settings. The use of crawler tractors, however, has been on the decline in New Zealand as grapple skidders have become favoured by most logging contractors. This research was a ground breaking step toward understanding logging fuel use as it provided logging companies with indicative proportions of rates of fuel use by phase of harvesting, which could be assumed as benchmarks: felling with chainsaw 5% (petrol), extraction 17%, loading 9%, secondary transport 68%, and unloading 1%.

Table 8: Fuel consumption by extraction machines (Gordon & Foran, 1980)

Extraction machine	Engine size (kW)	Fuel use rates (l/hr)	Fuel rates (l/kWhr)	Fuel (l/tonne)	Site terrain (slope)
Crawler tractor	110 – 150	24	0.18	0.6	Rolling terrain
Wheeled skidder	110 – 150	15	0.11	0.4	Flat terrain
Cable hauler	185 – 225	20	0.10	1.0	Steep terrain
Cable hauler	300 – 335	39	0.12	1.4	Steep terrain

A review on fuel consumption was later conducted by Amishev (2010) to help FFR develop fuel reduction strategies for forestry harvesting operations due to observed increases in fuel prices and harvesting costs in New Zealand. This followed an earlier study conducted by Sandilands et al. (2009) that associated increased greenhouse gas emissions with a reliance on fossil fuel by forestry machines during harvesting. Dash and Marshall (2011), with data collected from FFR members also studied logging fuel consumption rates under changing fuel prices to understand future implication associated with increased fuel prices in New Zealand. Their study showed that few logging companies' record fuel consumption associated with their logging activities and there is no standard procedure for data collection by logging crews. With advances in new engine technology and harvesting machines, more research is imperative to help logging industry in New Zealand to squeeze efficiency through fuel consumption.

2.9 Summary and conclusion of literature review

The literature review shows few studies have been conducted on rates of fuel use reported in unit of production (l/m^3) despite an increase in the level of logging mechanisation and the introduction of new logging machinery manufactured with improved engine technology. Published information of fuel use rates are based on old machinery with few studies reporting rates of fuel use by harvesting systems. This has made it difficult to develop a benchmark on rates of fuel use for decision making and planning purposes for new harvesting sites by modern machines and existing harvesting systems.

The review also shows that most research on fuel use has been done in the Scandinavian countries and the USA. Information gathered on published logging fuel use has also revealed inconsistencies regarding the units used in the denominator for reporting the average rates of fuel consumption by machines and harvesting systems. For example, different authors reported average fuel use by machines and systems as l/kW, l/SMH, l/PMH, gallons/PMH, l/m^3, gallon/ton, and/or l/tonne. Differences in common denominators as units of measure render results of previous research difficult to compare from an economic perspective.

It has also been observed that in the last decade, there have been numerous fuel use studies in the Southern US, Canada, Sweden, and Finland compared to New Zealand. The authors of these fuel use studies have embraced the concept of reporting rates of fuel use relative to unit volume of production as a common denominator for ease of economic comparison of harvesting costs. Majority of available published fuel consumption data from research conducted during the 1970s and 1980s are based on old machinery and need to be updated to be consistent with new logging machines made with new engine technology.

Moreover, published information on logging fuel use, due to lack of proper and adequate data, have not been able to report the effect of harvesting site factors such as slope, extraction distance, and piece size, on rates of fuel use. These factors form a significant component of harvesting variables that are assumed to influence rates of fuel use. With this background, an update on rates of fuel use with data obtained under known terrain and stand factors is necessary for improved economic efficiency in logging. In New Zealand, given the current shift towards full logging mechanisation, research on logging fuel use is necessary to offer a better understanding, and set benchmarks on fuel use for harvesting systems to be used as economic indicators given use of modern logging machinery.

Chapter 3: Methodology

The objective of this study was achieved by designing and conducting a logging fuel use survey with willing logging contractors across New Zealand that were keen to participate in the study to improve their understanding of logging fuel use. The survey lasted for a period of 14 months and involved the participation of 17 ground-based (GB) and 28 cable yarding (CY) logging contractors. The participating logging contractors were identified using industry contacts with the involvement of my supervisor, and then contacted through phone calls and emails.

Formal requests were then sent to the participants through emails attached with introductory information specifying the benefits of fuel use study for logging stakeholders in New Zealand (Appendix 1). It was explained to the participants that having a better understanding on logging fuel use would help them to optimise machine and harvesting system selection for operational efficiency and economic viability through improved decision making and planning. The participants were further assured of their confidentiality, that the information provided would be used purposely for academic research, and that they would be updated on the study progress and results. During the survey, close monitoring and participatory reminders were made through phone calls, emails, and personal contacts for the purposes of data acquisition and participant engagement in the study. The summary of survey process, data collection and monitoring is outlined in Figure 3.

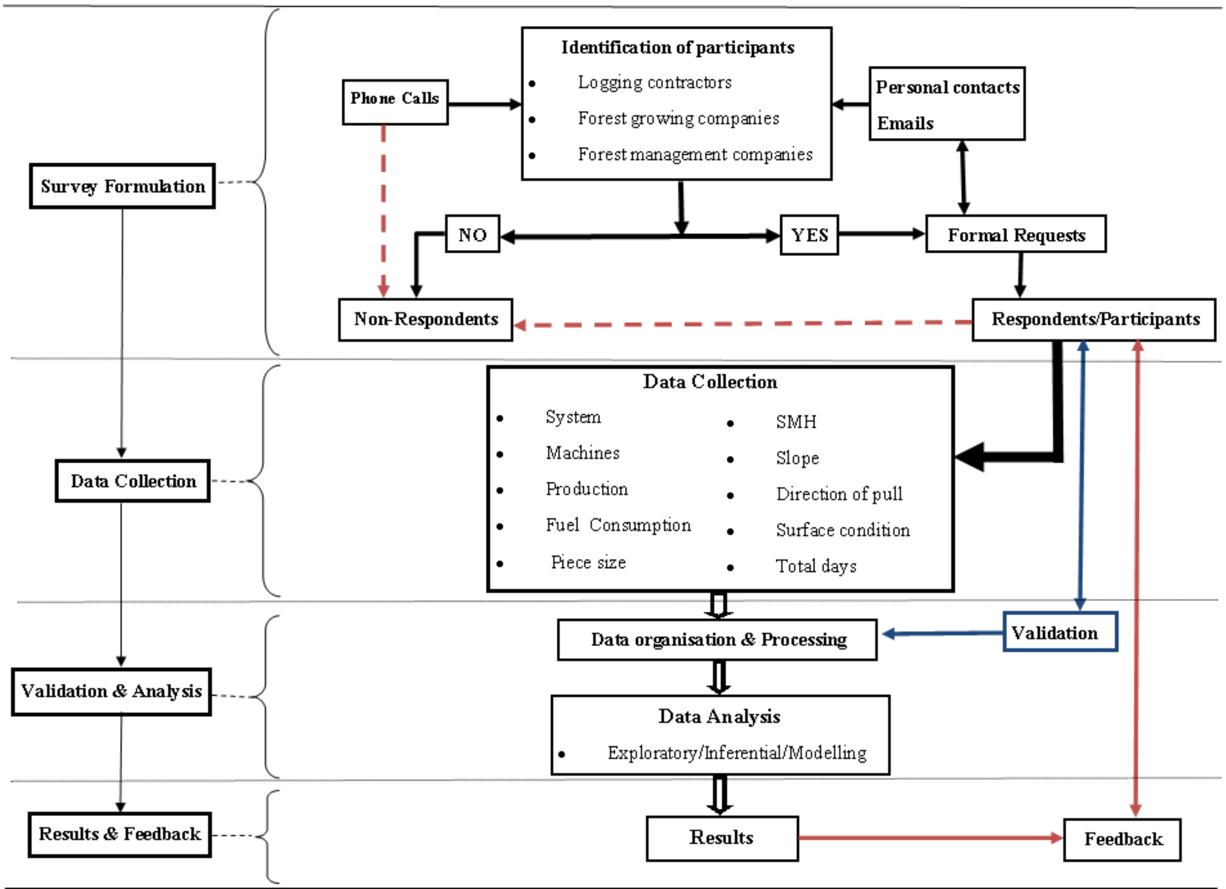

Figure 3: Survey process and monitoring

3.1 Study area and description

Geographical location of New Zealand

The study was designed and conducted through a fuel use survey in New Zealand, which is made up of two islands, the North and the South Islands, both located and stretching between latitudes 29^0S to 53^0S, and longitudes 165^0E to 176^0E, to the South East of Australasia. The country experiences four annual climatic seasons, with dry conditions during summer to wet in winter. These seasons are important in logging planning as they determine the efficiency of forestry harvesting operations due to their influence on ground characteristics of the harvest sites. Ground characteristics of a harvesting site such as soil moisture affect machine traction and tree accessibility.

Distribution of participants across New Zealand

Data was obtained across both the South and the North Islands. Regional distribution by data source were developed using geospatial tools in ArcGIS from a territorial map layer obtained from Land Information New Zealand (LINZ, 2015). The feature classes (Figure 4) showing GB and CY logging crews and regional locations of harvesting operations as defined according to NZFOA's wood volumes and forest distributions (NZFOA, 2012). The distribution of these crews across the country illustrates typical logging operations on steep slopes for CY systems and harvesting operations on sites with flat and rolling slopes for GB crews. The distribution of participating contractors shown in Figure 4 only indicate regional sources of survey data and 'NOT' the exact location of the actual participating logging contractors in the study for the purposes of confidentiality.

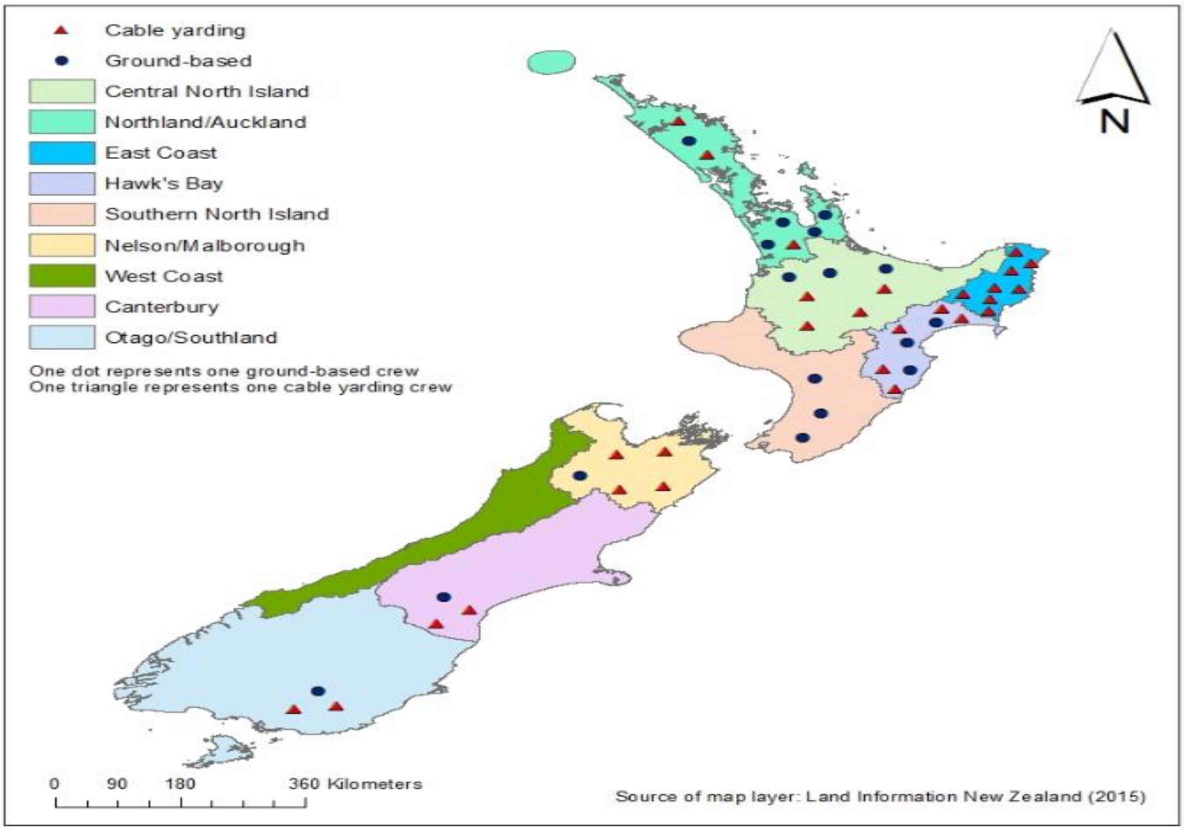

Figure 4: Regional distribution of crews surveyed. Map developed to NZFOA Forest Regions (NZFOA, 2012)

Typical New Zealand harvesting sites

New Zealand topography is a result of volcanic landforms evidenced by numerous undulating landscapes and expansive plains and ground surfaces made of characteristic loess soils (Visser et al., 2014). The traction properties of these loess soils are heavily dependent on moisture levels and very important for machine traction and manoeuvrability during logging. These landscape features are characterised with high country steep slopes of up to 70% and flat to rolling sites of 15 to 30% slope, where most of commercial forest plantations are established and tended for future harvesting (Visser et al., 2014). Harvesting site slopes form an integral component for decision making during logging planning, and dictate the type of harvest system to be selected and choice of equipment (Visser, 2010). Some forest plantations are established in very steep slopes that are sometimes dangerous and difficult to operate on with machines. With the tree value recovery notwithstanding, operations in such steeper slopes must also comply with safety and environmental standards set by regulatory authorities, and be economically feasible to logging planners. The two common logging systems preferred under New Zealand conditions are usually conducted under distinct site slopes, with CY mostly planned on slopes greater than 35% (Figure 5). GB operations on the other hand are planned and executed on sites with flat and rolling slopes of between 0% and 30% slope, as in Figure 6 showing a CAT grapple skidder on a rolling harvest site. Some GB harvesting operations are also occasionally conducted on near steep slopes.

Figure 5: Typical CY set up in a steep country

Figure 6: Skidder operation on a rolling site

Harvesting site factors and categories

Harvesting site factors such as slope, surface conditions, and direction of pull during extraction, were categorised on the assumption that each factor differently affects the average rate of fuel consumption during harvesting. Extraction methods were also assumed to vary between CY and GB systems with logs or stems pulled towards landings on respective harvest sites located in different directions relative to felling site. Logging operations are also conducted on sites with varied soil moisture conditions. For example, extraction on a flat harvest site is assumed to be easier than that on a steeper site. Similarly, pulling or skidding of logs or full stems up the slope is less efficient and more difficult than pulling downhill due to effects of direction on gravitational pull. Consequently, machine traction on dry and wet ground conditions may be different. Various categories of harvest sites were adopted in this study under these extraction scenarios irrespective of system of harvesting. Figure 7 shows different grapple skidders working under different harvesting sites and ground conditions. Skidder on site A is skidding uphill under moist conditions, skidder B on uphill under dry conditions, skidder C on a flat site on wet ground, and finally skidder D skidding downhill under dry conditions.

Figure 7: Skidding on different harvesting sites and surface moisture conditions. Skidders: A skidding uphill on moist conditions, B uphill on dry conditions, C on a flat site on wet site, and D downhill under dry surface conditions

Site slopes were categorised into flat, rolling, and steep; direction of pulling into flat, uphill, downhill and variable; and finally surface conditions into dry, dry/moist, moist/wet, variable, and wet (Figure 8), as provided for in data collection sheet (Appendix 2).

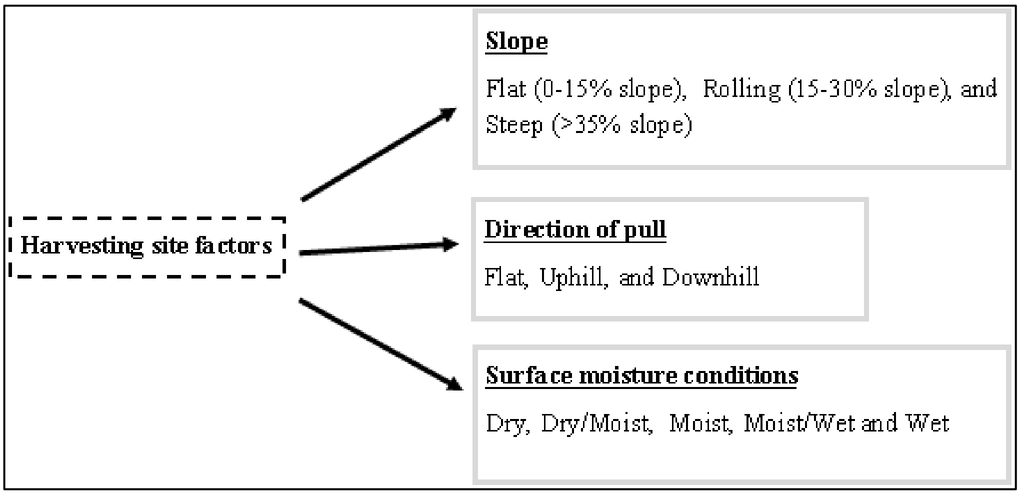

Figure 8: Categories of various harvest sites factors for the survey

3.2 Data collection and organisation

The participating logging contractors were asked to provide information on fuel use and production data for the year 2013 or 2014. Participants were required to give basic information on all the fuel used and total production by month or total for the year by crew, and/or give data on total daily and/or weekly fuel supply and production volumes by machines for the specified duration of harvesting in the survey, to achieve some degree of temporal resolution for the survey as outlined in Table 9. Information on the target attributes are outlined in Appendix 2.

Data collection began in May 2014 and through July 2015. Most logging contractors provided information on crew’s fuel use and production by month and a few contractors by year (2013 or 2014). Only one GB crew provided daily fuel supply and production data by individual machines for the year 2013. Some of the participating contractors provided additional information on basic system description and further specified other operation(s) and system adjustments for the duration of data supplied. These adjustments and modifications included two-staging operations, roadside recovery, modification of rigging configuration and type of difficulty of the operations, that were useful for interpretation of the results during analysis.

Table 9: Survey variables/factors and target attributes

Survey Variable	Expected attribute
Type of harvesting system	Ground-based (GB) or Cable yarding (CY)
Production (m^3 or in metric tonnes*)	Daily, weekly, monthly, yearly total production by system and machines
Fuel consumption (l)	Daily, weekly, monthly, or yearly total fuel supplied by system and machines
Piece size (m^3 or in metric tonnes*)	Average size of logs or stems handled for the duration stated in *tonnes or in m^3
Extraction distance (m)	Average skidding or yarding distances by system of harvest
Direction of pull	Skidding or yarding on flat, uphill, or downhill sites by system
Slope or terrain features	Harvesting on various sites: flat (0 – 15% slope), rolling (16 – 30% slope), and steep (>36% slope)
Surface conditions	Skidding or yarding on dry, wet, or moist sites
Machine data	Type, make, model, average power rating, and SMH
Duration of harvest	Days per week, month, or year

**One metric tonne is assumed to be equivalent to 1 m^3*

Data obtained on all survey attributes from the survey participants were then organised in Excel spreadsheets (data management package in Microsoft office), with crews identified as either GB or CY under separate column headings. The GB and CY crews were then identified by type of harvesting system in a separate column for ease of data management. The observed monthly or annual numerical data and factors associated with each crew, such as average extraction distance, direction of pull, surface conditions, average slope, piece size, fuel consumption and production, were then recorded in each cell in the Excel spreadsheet. Entries were also made for each crew for machine data indicating the number used, average power, SMH and total days worked by month or year. More columns were created for response variables derived from the information obtained on production, fuel consumption, and average power. These variables included; the total power in kilowatt hour (kWhr), the average fuel consumption in litres per kilowatt-hour (l/kWhr), and average fuel consumption in litres per unit of production (l/m^3) by crew. Rates of fuel use in l/m^3 and l/kWhr as the main response variables for the study were then derived from fuel use, production, and power rating data. For the purposes of uniformity during data analysis, rates of fuel use in l/m^3 and l/kWhr were derived from yearly data by harvesting systems for all the study data, with monthly data on production and fuel use by each crew expressed on a yearly basis.

Numerical entries of all study data and derived response variables (rates of fuel use in l/m^3 and l/kWhr) were made in a single excel spreadsheet and confirmed with the actual contractor data through phone calls. Scatter and boxplots were used as statistical tools in R software to check for the normality of the distribution of data, and identify outliers from the data supplied by the contractors for purposes of cross-matching. For cases of inconsistent data entries, participating contractors were contacted for clarification of the entries as the true observations of their records. This ensured that correct entries of numerical data and observations were made with some degree of validity.

3.3 Determination of average rates of fuel use by crews and harvesting systems

To determine the monthly or yearly average fuel consumptions rates by harvesting crew and/or harvesting system, mathematical algorithms were used to compute total harvesting production volumes in cubic metres, total quantity of fuel used in litres and total power in kilowatt hour by the year of harvest from crew data (Figure 9). Monthly data on fuel supply and use by individual crew were then combined to give annual representation of total fuel use for a single harvesting system in the survey. Similarly, monthly data on production by individual crew were also combined to represent an annual production data for a single harvesting system in the survey. Total production in cubic metres and total fuel used in litres were determined from all study data as the sum of all monthly or yearly observations, respectively. Total power drawn by all machines by system of harvest was obtained as the product of average system power, SMH, and total days worked per year. All the GB crews were grouped as GB harvesting systems, and all the CY crews were grouped as CY harvesting systems based on annual fuel use and production data. Every harvesting system was matched with survey attributes relating to piece size, extraction distances, number of machines used, power rating, slope, direction of pull, surface moisture conditions, SMH and number of harvesting days per year, consistent with original crew data. Average minimum and maximum fuel use, production, number of machines used, power rating, extraction distances, SMH and harvesting days were also determined for both GB and CY harvesting systems from the combined annual survey data. Rates of fuel consumption by harvesting systems for all study data were determined as response variables to meet study objectives and verify null and alternative hypothesis. Rates of fuel use were determined as:

a) Average fuel consumption in litres per unit volume of production (l/m^3) and in litres per unit of power in kilowatt hour (l/kWhr) by crew and/or harvesting system as main study response variables and measures of operational efficiency.

b) Average fuel consumption in l/m^3, l/kWhr, and SMH by harvesting machines using daily machine fuel supply and production data from a single GB crew.

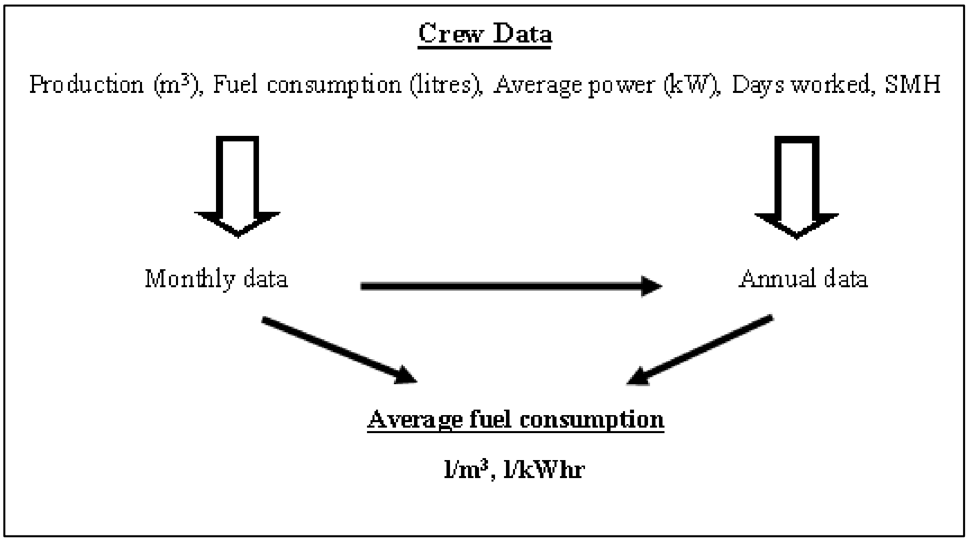

Figure 9: Crew data analysis and determination of average fuel use rates

Average fuel consumption by harvest system

For all study data on fuel use and production, all GB and CY crews were classified as GB and CY harvesting systems, respectively, using year as a baseline. Average fuel consumption rates were determined in two ways: (1) as a weighted average for all the 17 GB and 28 CY harvesting systems combined, using total fuel consumed divided by total production, and (2) as the average fuel consumption based on average consumption by each individual 17 GB and 28 CY harvesting system, obtained by dividing the total fuel used by the total production for each harvesting system. The latter was taken as the benchmark average fuel consumption rates for all 17 GB and 28 CY harvesting systems in New Zealand. For each harvest system, fuel consumption efficiency was taken as a measure of quantity of fuel used relative to unit of production (l/m^3) and/or unit of kilowatt hour (l/kWhr).

Definitions of some terminologies used

Logging crew is the basic operational unit of a harvesting system combining the use of various machines to fell, process and load log grades on log trucks on landings at a specified forest setting.

Harvesting system is a combination of all machines used by a logging crew during harvesting operations under purely skidding or cable yarding extraction methods assumed suitable for a given harvest setting determined by slope.

Average fuel consumption in litres per unit of production is the quantity of fuel consumed in litres to harvest a unit volume of timber determined by month or year, and expressed as l/m^3.

Average fuel consumption in litres per unit power is the quantity of fuel consumed in litres per unit of power drawn by all harvesting machines relative to average harvesting system power rating, and expressed as l/kWhr.

System or crew fuel consumption efficiency is taken as the quantity or intensity of fuel used in litres by a harvest system or harvesting crew relative to unit of production (m^3) or power rating (kW) as an indicator of economic viability in logging operations (Sundberg & Svanqvist, 1987) and level of harvesting difficulty.

3.4 Determination of average rates of fuel use by machines

Average fuel consumption in litres by machine was determined per unit of production, per unit of power in kilowatt, and per SMH using daily fuel supply and production data (Figure 10) for a fully mechanised high production GB crew. To derive machine fuel consumption variables, all the daily fuel supplied and production handled by each machine was added separately for the year 2013. Individual machine average fuel consumption was then determined by dividing the total quantity of fuel used in litres for the harvesting year by the total volume of timber handled during for the same year of harvest. Using daily SMH, power rating in kW, and number of days worked for the year, this study determined total fuel used and total production, individual machine fuel consumption in litres, and overall fuel consumption efficiencies in l/SMH, l/m^3, and l/kWhr. Additional information provided on the number of machines and power ratings was used to determine average number of machines and power for the GB harvesting crew. However, for crews that only listed machines by type of operations, such as a harvester, skidder, processor and front-end-loader, published information by FORME (2012) was used to allocate average power rating for the machines surveyed. Rates of fuel consumptions determined by machine from the study data were then compared with annual published machine data by FORME (2012).

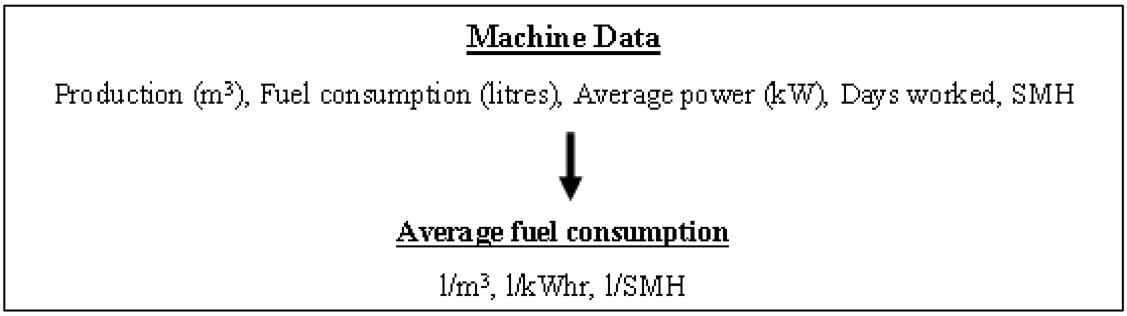

Figure 10: Machine data analysis and determination of average fuel use rates

3.5 Southern US logging fuel use study

A separate set of logging fuel use study data collected between September 2013 and May 2014 in the Southern US was received courtesy of institutional relationships between my supervisor and his research colleague at Auburn University in Alabama. The Southern US researchers collected data on fuel use and production from various logging crews in Alabama, Georgia, Florida, North Carolina, Louisiana, and Mississippi, plus Ohio at the eastern extent of the Midwest (Figure 11). This data was used by the researchers to determine the factors affecting fuel consumption and harvesting costs in the Southern US. The study targeted data on various harvesting attributes (Appendix 4) by crew including, but not limited to, tract size, type of cut, tree species and diameter, slope, soil moisture level, and total harvested volume. Data was also provided on machine/equipment attributes such as type, year of manufacture, make, and model. Every crew surveyed had a feller-buncher, skidder, loader, standby loader, and mini processor machines, each associated with total fuel used, and total production volumes handled. The operations involved thinning and clear-cutting targeting three main log products of pulpwood, chipper logs, and sawn-timber classified by crews as the main merchantability grades. Actual data of the Southern US logging fuel use study and some key results can be accessed at a publication by Kenny et al. (2014).

The Southern US logger fuel use survey data on production and fuel use was obtained from 18 logging crews by tract and on weekly basis. In terms of data contribution to the survey by each of the southern states shown (Figure 11), Alabama provided the highest proportion of fuel use and production data (48%), Ohio (17%), North Carolina (13%), Florida (11%), Louisiana (8%), and Georgia (3%). Six Alabama crews provided weekly production and fuel use data, with only 3 GB crews showing a complete fuel use and production data for 2013. The weekly and monthly production and fuel supply data obtained from all of the 18 Southern US GB crews were then scaled to annual data by multiplying weekly data by 50 standard harvesting weeks (i.e. 250 days/year), and monthly data converted to yearly data for the purposes of uniformity and comparative analyses with New Zealand GB crews. One of the Southern US crews with production and fuel use data by tract (area harvested) from the state of Mississippi could not be scaled to annual metrics, due to unspecified period of harvesting in the data, and was therefore left out of the analyses and comparison with New Zealand GB crews.

All the study data on production (in USA short tons) was then converted to standard metric tonnes and fuel used (in USA gallons) to standard litres for conformity to international standard units of measure and, for purposes of comparison with New Zealand GB fuel use study. The Southern US dataset for each crew was then classified by type of cut as either thinning or clear-cutting or both for the study. From all the study data, 6 crews conducted both thinning and clear-cutting operations, while 3 and 9 crews worked purely on thinning and clear-cutting operations, respectively. The New Zealand fuel use study results were compared to those of the Southern US GB crew based on the assumption of similarity in terms of: harvesting systems (conventional or GB), type of machines used, harvesting mainly pine plantations (though state of Ohio is known for hardwood production), irrespective of geographical locations during the comparative analyses.

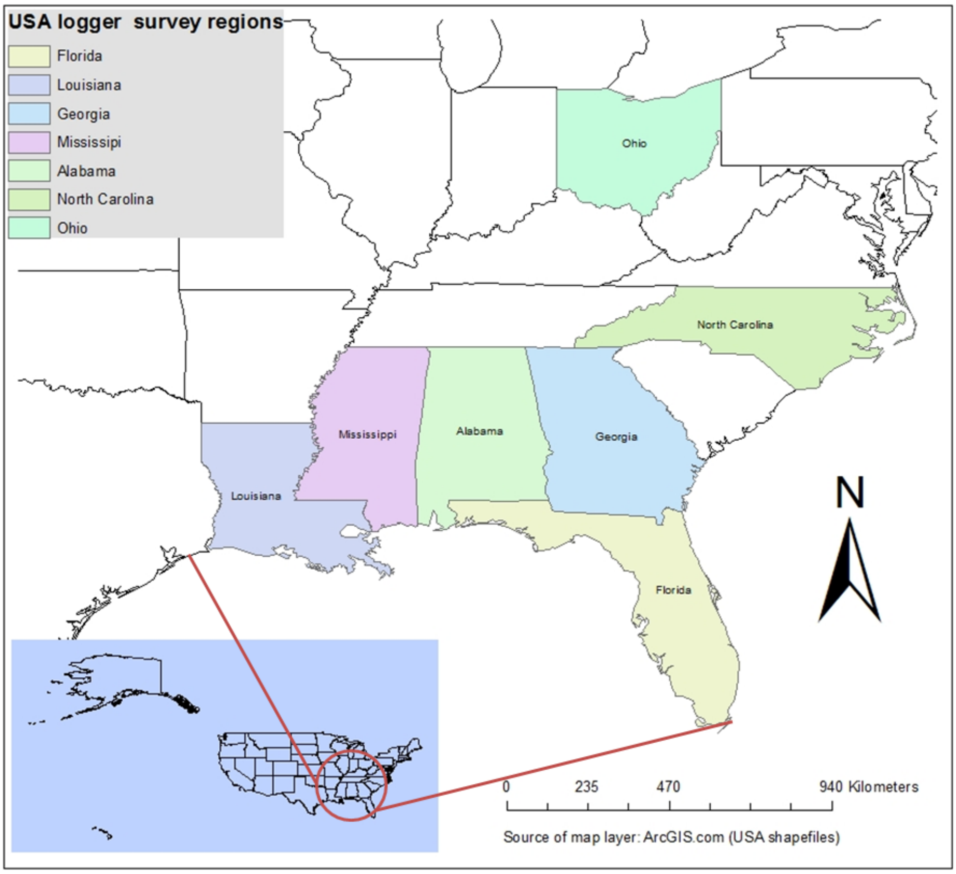

Figure 11: South USA logger fuel use survey and data collection regions

3.6 Analyses of results

All the study data was organised in Microsoft excel and explored using in-built statistical packages for numerical summaries, linear models and trends, and then organised for compatibility with R programming language, and then imported into R statistical software for further exploratory and inferential analyses and statistical diagnostics for linear modelling. Descriptive statistics for measures of central tendencies such as mean, standard deviation and quartile ranges of the response variables (the average rates of fuel consumption in l/m^3 and l/kWhr) by harvesting system and machines were then determined using the numerical summaries package in R. Simple linear and power function relationships were used to establish linear correlation (if any) between rates of fuel use in l/m^3 or l/kWhr (as main response variables) and predictor variables/factors in the study. The correlation coefficients from the linear relationships were then used to identify factors that showed influence on rates of fuel use during harvesting for purposes of significance tests and modelling.

Analysis of variance (ANOVA) was performed to establish if individual predictor factors/variables such as type of harvesting system (GB or CY), total production, number of machines used, average power rating, slope, direction of pulling during extraction and surface moisture conditions had any significant effect on rates of logging fuel use in l/m^3 or l/kWhr during harvesting operations at 95% test level of confidence (α=0.05). Analysis of covariance (ANCOVA) was further employed to test for any significant effect of various levels of slope (flat, rolling and steep), directions of pull (typically flat, uphill and variable) and surface moisture conditions (dry, moist, dry/moist, moist/wet and wet) as covariates in determining rates of fuel use during harvesting for all study data. T-tests were used to test for any significant differences in average rates of fuel use between GB and CY systems of New Zealand. Differences in average fuel consumption rates between New Zealand and the Southern US GB crews were also determined suing t-tests. Fuel consumption relationships in l/m^3 and total annual production were determined to establish whether scale of production had a significant influence on rates of fuel use between GB and CY systems in New Zealand, and similarly between New Zealand and Southern US GB crews.

Statistical diagnostics in R were used to check for normality, independence and equal distribution of variances in the data using plots of residuals of main response variables (rates of fuel use in l/m^3 and l/kWhr). The following linear model was subjected to step regression under the assumption of independent and equal variances in normally distributed data to predict rates of fuel use in l/m^3 and l/kWhr using study data.

$$Y \sim \beta_1 SYS + \beta_2 PRD + \beta_3 PSC + \beta_4 MAC + \beta_5 PWR + \beta_6 ETD + \beta_7 SLP + \beta_8 DRP + \beta_9 SFC + e$$

Where Y (taken as the main response variable) is the rate of fuel use in l/m^3 or l/kWhr, $\beta_1 ... \beta_9$ are linear slopes of each predictor variable in the model, *SYS* is harvesting system, *PDR* is production, *PSC* is piece size, *PWR* is average power, *ETD* is average extraction distance, SLP is slope of harvesting site, DRP is direction of pull during extraction, and *SFC* is surface moisture condition with *e* representing the residual error associated with all predictor variables in the model. Regression coefficients (linear slopes) obtained from the linear model was used in the final predictor model to predict rates of fuel use in l/m^3 or l/kWhr. Process stages for exploratory data analyses and statistical diagnostics for developing linear predictor model for logging fuel use rates outlined in Figure 12. Results of this study were summarised, organised and presented using tables, figures, scatter plots and boxplots to show the observable differences and variability.

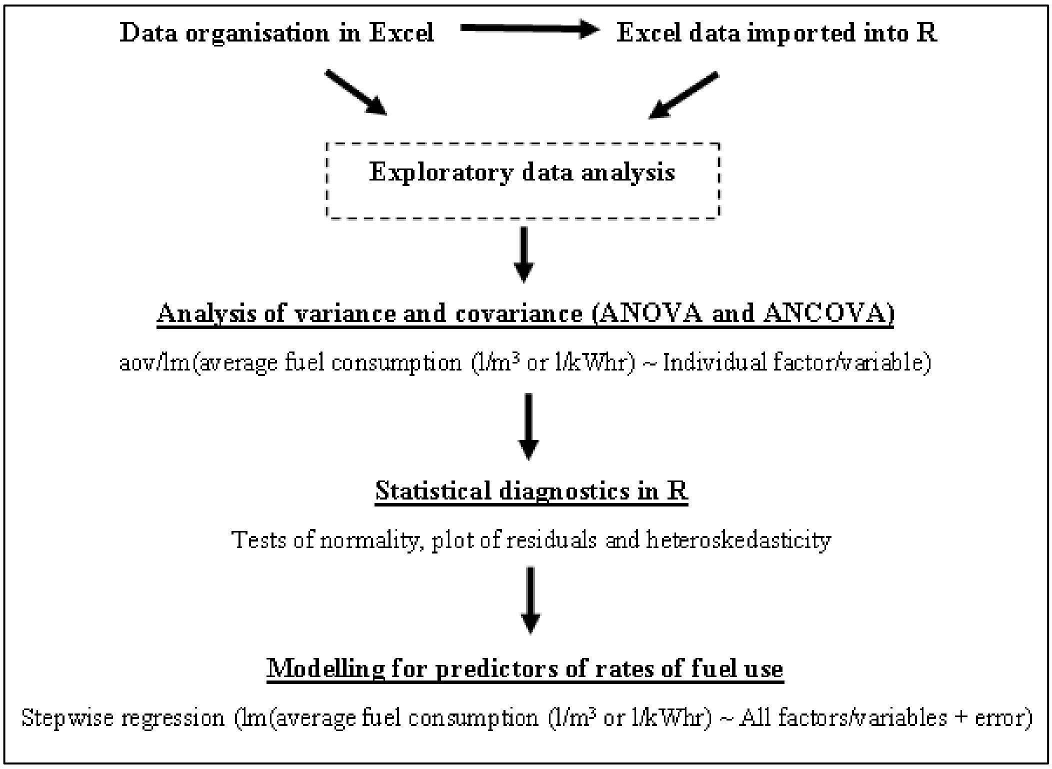

Figure 12: Data preparation, diagnostics, tests of significance and modelling processes

Chapter 4: Results

A total of 45 logging contractors participated in the survey conducted from June 2014 to July 2015 across New Zealand. During the survey, 17 ground-based (GB) and 28 cable yarding (CY) crews shared information on their fuel use and production data. By type of harvesting system, seven GB crews provided fuel use and production data by month for the harvesting year 2013. However, there were no GB crews with monthly data on fuel use and production for the year 2014. Fuel use and production data by year of harvest was provided by 4 GB crews for the year 2013 and 6 crews for the year 2014. In total, 11 GB crews supplied fuel use and production data by month (for 2013 data) with only 6 crews sharing information on total production and fuel by year of harvesting for the entire survey period. A summary of monthly average, including minimum and maximum fuel supply for 11 GB crews is shown in Table 10. The lowest average fuel supply was recorded in December and the highest in July for all the 2013 dataset.

Table 10: Combined fuel supply and use by month for GB crews (2013 data, n=11)

	Fuel supply and use (l/Month)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	16,100	10,600	24,000	5,080	32
Feb	17,200	11,700	28,000	5,500	32
Mar	18,000	8,900	27,000	7,100	40
Apr	19,000	10,680	31,300	7,060	37
May	20,000	12,500	27,650	6,300	31
Jun	17,300	11,500	24,000	5,070	29
Jul	20,200	12,200	29,380	6,390	32
Aug	17,900	10,600	23,650	4,930	28
Sep	19,400	11,300	24,200	4,880	25
Oct	19,100	10,200	24,500	5,260	28
Nov	17,500	5,450	23,200	7,500	43
Dec	12,200	3,200	18,100	5,080	42

January and December showed the lowest average monthly production with high variations for a single crew compared to the other months across the harvesting year (Table 11). The highest monthly average production by a single GB crew was 18,800 m^3 recorded in the month of July 2013. Generally, all 11 GB crews' monthly fuel use and production data (2013 data) showed high variations across the year with the lowest variation at 62% in August.

Table 11: Combined production data by month for GB crews (2013 data, n=11)

	Total production (m^3/month)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	5,040	1,400	13,600	4,100	82
Feb	6,220	1,900	13,600	3,900	63
Mar	6,700	1,800	15,940	4,700	70
Apr	6,800	1,800	17,400	5,100	75
May	7,280	1,600	17,800	5,090	70
Jun	5,900	2,040	14,100	4,000	68
Jul	7,700	2,900	18,800	5,300	69
Aug	7,200	3,800	16,900	4,500	62
Sep	7,000	3,800	17,100	4,730	68
Oct	6,300	3,450	16,300	4,600	73
Nov	7,300	4,100	16,600	4,700	65
Dec	4,500	1,300	12,300	3,700	81

Combined fuel use and production data by month was provided by 12 CY crews for the year 2013 and three (3) crews for the year 2014. Four CY crews supplied fuel use and production data for the year 2013 and 9 CY crews for the year 2014. In total, 16 CY crews provided fuel use and production data by month and 12 crews by year. Monthly data for all CY crews for the year 2013 showed the lowest average fuel supply for a single CY crew in February and December, with maximum fuel supply of 30,500 litres for a single crew in May. There was a variability of 56% in fuel supply for all the CY crews combined in January compared to variability in fuel supply during the other months of the year 2013 (Table 12). This variability in January was associated with the slow pace of start of year operations associated with low production. January was also observed to have surplus or carryover fuel from the previous year added to beginning of new harvesting year supplies of fuel. The lowest supply by most crews in December was associated with reduced harvesting operations and preparation for end of year closure of harvesting operations.

Table 12: Combined fuel supply and use by month for CY crews (2013 data, n=12)

	Fuel supply and use (l/month)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	14,300	6,900	31,950	7,960	56
Feb	14,100	9,900	24,700	4,770	34
Mar	15,200	8,700	24,500	4,990	33
Apr	15,100	8,500	23,500	5,300	35
May	18,200	11,300	30,500	6,800	37
Jun	14,100	9,000	25,400	5,800	41
Jul	17,500	8,600	28,820	5,800	33
Aug	18,100	9,800	30,200	6,400	36
Sep	15,300	8,900	25,530	5,750	38
Oct	16,500	10,200	30,300	7,000	42
Nov	15,190	8,900	29,400	6,760	44
Dec	9,960	4,400	15,800	3,300	33

Similarly, January and December recorded the lowest combined average total production by month for any single CY crew compared to total production by the remaining months of the year 2013. The highest monthly production of 5,870 m^3 corresponding to high fuel supply for a single CY crew was recorded in May. This gave an indication of more intensive production operations during May by CY crews. There was also more variability in average production in January (46%), November (47%) and December (42%) as shown in Table 13.

Table 13: Combined production data by month for CY crews (2013 data, n=12)

	Total production (m^3/month)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	3,560	1,480	7,070	1,640	46
Feb	4,400	3,200	8,570	1,640	37
Mar	4,950	3,050	8,360	1,710	35
Apr	4,850	2,960	7,770	1,570	32
May	5,870	3,600	9,970	2,120	36
Jun	4,760	2,800	8,080	1,600	34
Jul	5,700	3,100	10,280	2,060	36
Aug	5,700	2,400	9,850	2,060	36
Sep	5,100	2,800	9,880	1,960	39
Oct	5,450	3,110	9,900	2,060	38
Nov	5,300	2,600	9,300	2,470	47
Dec	3,370	1,900	5,930	1,410	42

Combined average fuel use and production data by month for 3 CY crews for the year 2014 were similar in pattern to CY crew data in 2013. Total annual fuel supply for all the 3 CY crews combined ranged from 2,600 to 21,400 litres per month. On average the lowest monthly fuel supply was 5,800 litres and a maximum of 14,800 litres. Fuel supply for CY crews in December 2014 showed a variability of 50% compared to 12% variability for fuel supplies in January. Average production data by month for 2014 showed that a single CY crew produced a minimum of 1,600 m^3 and maximum of 5,400 m^3. Lowest average production was recorded in January (2,500 m^3) and December (2,600 m^3) with the highest average production of 4,100 m^3 in September 2014.

4.1.1 Summary of study data by harvesting system

There was 60% variability in total annual production for all the GB harvesting systems combined, with total annual production ranging from 26,100 to 190,200 m^3. Total annual production, total annual fuel use, and average extraction distances for all the GB harvesting systems combined were more variable than the number of machines used, average systems power, piece size, SMH and number of harvesting days per year as shown in Table 14. However, variations in SMH and number of harvesting days per year remained almost similar. In terms of number of machines, the largest GB harvesting system had six machines, working for up to 10 SMH per day. Most GB systems handled average piece sizes ranging from 1.1 to 2.9 m^3 skidded up to maximum skidding distances of 400 m.

Table 14: Study data for all the GB harvesting systems combined (n=17)

Study variable	Average	Minimum	Maximum	SD	Variation (%)
Fuel (l/year)	172,800	104,700	271,100	53,700	31
Production (m^3/year)	65,000	26,100	190,200	39,200	60
Number of machines	4.5	3	6	1.2	28
Average power (kW)	137.7	111.7	173.6	18.1	13
Piece size (m^3)	1.9	1.1	2.9	0.4	20
Extraction distance (m)	249	150	400	75	30
SMH	8.7	8	10	0.7	8
Days/year	217	180	247	17	8

Combined survey data for all the CY harvesting systems on average showed that a single crew worked for 226 days with between 3 and 8 machines for every single operation and handled piece sizes ranging from 1.1 to 3.5 m^3. Annual total production by a single CY harvesting system varied from 32,400 to 92,500 m^3, with total annual fuel use ranging from 95,800 to 292,500 litres. Summary of key attributes for the combined annual data for all the CY systems is shown in Table 15.

Table 15: Study data for all the CY harvesting systems combined (n=28)

Study variable	Average	Minimum	Maximum	SD	Variation (%)
Fuel (l/year)	165,500	95,800	292,500	49,400	30
Production (m^3/year)	52,400	32,400	92,500	15,400	29
Number of machines	5.1	3	8	1.3	25
Average power (kW)	183.2	161.1	229.7	20	11
Piece size (m^3)	2.2	1.1	3.5	0.4	20
Extraction distance (m)	264	180	400	69	26
SMH	8.6	8	9.5	0.5	6
Days/year	228	200	263	16	7

All study data by GB and CY harvesting systems compared

All the study data collected during the survey represents a combined total annual production of approximately 2.6 million cubic metres of final grade logs predominantly radiata pine (*Pinus radiata*) harvested using approximately 7.6 million litres of fuel, for harvesting operations conducted between January 2013 and December 2014 by both 17 GB and 28 CY harvesting systems in New Zealand. This study data on total annual production represents approximately 10% (NZFOA, 2012) and 9% of total annual harvested wood volumes in New Zealand (NZFOA, 2014). All the GB harvesting systems combined harvested approximately 1.1 million cubic meters of timber using 2.94 million litres of fuel. Similarly, all the CY harvesting systems combined harvested wood volumes of approximately 1.5 million cubic metres by consuming approximately 4.6 million litres of fuel. GB harvesting systems harvested an average of 64,900 m^3/year while CY systems produced 52,400 m^3/year, however, there was no significant difference in average annual rates of production between GB and CY harvesting systems (p-value=0.22).

A combined total of 219 machines with an average power of 160.7 kW were used for the period covered by harvesting data. All the logging crews combined worked at an average of 8.7 hours/day for 223 days a year (Table 16). By individual harvesting system, the average number of machines used by a single CY harvesting system was 5.1 while that for all the GB harvesting systems was 4.5. The average number of machines used between GB and CY harvesting systems were however, not significantly different (p-value=0.12). On the other hand, the average power rating of all the GB harvesting systems combined was 137.7 kW compared to 183.7 kW for all the CY harvesting systems. The average power ratings between all GB and all CY harvesting systems were significantly different (p-value<0.0001). This significant variation in average power rating between the two harvesting systems was attributed to differences in machines used with the use of cable yarder machines for CY systems and grapple skidders for GB operations that are generally manufactured with varied power ratings. It was further observed that GB harvesting systems generally tended to work for longer hours a day and fewer days a year than CY systems (Table 16).

Table 16: All study data for both GB and CY harvesting systems compared (n=45)

Study variables/factors	Ground-based	Cable yarding	Combined
Total harvesting systems	17	28	45
Total fuel (l)	2,937,200	4,633,200	7,570,400
Total production (m^3)	1,103,800	1,467,800	2,571,600
Annual average production (m^3/year)	64,900	52,400	58,700
Total number of machines	76	143	219
Average number of machines	4.5	5.1	9.6
Average power (kW)	137.7	183.7	160.7
Average SMH/day	8.7	8.6	8.7
Harvesting days per year	217	228	223

Summary of data by harvesting site factors

Ground-based (GB) operations were conducted on production forests established on typically flat (0-15% slope) and rolling slopes (16 to 30% slope), while cable yarding operations were conducted predominantly on steep slopes (>35% slope). Grapple skidders were used for skidding average piece sizes of 1.9 cubic metres on flat, uphill, and variable directions of pulling toward landings situated at average extraction distances of 249 m from the stump site during extraction. Extraction by CY harvesting systems involved yarding average piece sizes of 2.2 cubic metres by skyline suspension systems under different rigging configurations using cable yarder machines. During yarding, stems and/or logs were pulled exclusively in uphill directions toward landings located an average extraction distance of 264 m from felling sites. Data showed some variations on average extraction distances as some GB and CY crews also operated on harvesting sites with longer average extraction distances of between 400 m and 1000 m mostly considered difficult and occasionally involved two staging operations. Paired t-tests showed no significant difference in average piece sizes handled (p-value=0.08) and average extraction distances (p-value=0.49) between GB and CY harvesting systems. Data also show that GB and CY harvesting operations were executed on dry, dry/moist, moist, moist/wet, wet, and variable surface moisture conditions. Summary of stand and terrain variables for the study are shown in Table 17.

Table 17: Summary terrain and stand data for GB and CY harvesting systems (n=45)

Stand and terrain variables	**Ground-based**	**Cable yarding**	**Combined**
Average piece size (m^3)	1.9	2.2	2.1
Average extraction distance (m)	249	262	256
Typical direction of pull	Flat/Uphill/Variable	Uphill	Flat/Uphill/Variable
Typical slope	Flat/Rolling	Steep	Flat/Rolling/Steep
Typical surface conditions	Dry, Dry/Moist, Moist, Moist/Wet, Wet, and Variable		

4.1.2 Summary study data by level of mechanisation

Even though the survey never targeted data by level of mechanisation for the two harvesting systems, the data obtained contained information on types of mechanisation by type of harvesting crew. Crews surveyed were neither fully motor-manual nor fully mechanised but existed as combinations between motor-manual and mechanised type of operations. Using this information on mechanisation, crews in this study were grouped as motor-manual, fully mechanised, and a combination of motor-manual and mechanised (Table 18) to establish impacts of mechanisation on rates of fuel use. GB operations data contained 59% fully mechanised, 24% fully motor-manual and 18% mixture of manual and mechanised harvesting operations. Eighty six percent of CY operations in the data contained single operations with motor-manual felling and mechanised processing. The remaining 16% CY operations were grouped as fully manual, fully mechanised and/or alternative combinations of both as contained in the dataset.

Table 18: Proportions of harvesting systems by type of mechanisation (n=45)

	Ground-based		**Cable logging**	
Type of mechanisation	Number	%	Number	%
Motor manual	4	24	1	3.5
Fully mechanised	10	59	2	7
Manual felling + Mechanised processing	3	18	24	86
Mechanised felling + manual processing	0	0	1	3.5
Total	***17***	***100***	***28***	***100***

Data on CY operations further contained 89% motor-manual felling by chainsaws and 11% mechanised felling by feller-bunchers and harvesters. Similarly, there was 41% motor-manual and 59% mechanised felling by all the GB operations combined. There was also 93% and 76% mechanised processing by CY and GB systems, respectively contained in the dataset, with also 7% and 24% motor-manual processing contained in CY and GB operations, respectively. These results on mechanised processing for this study (n=45) suggested an increase in mechanised processing in comparison to annual harvesting benchmarking data by (Visser, 2011, 2013, 2015).

4.1.3 Ground-based crew fuel use and production data by machines

Data used in machine fuel use analyses was obtained from a fully mechanised high production GB crew operating with six machines: two CAT 324/325C harvesters, a single CAT 545C grapple skidder, a Komatsu PC300 excavator fitted with processing head, one CAT 938F and one CAT 938G front-end loaders during the harvesting year of 2013. These machines were of different make, average power rating in kilowatt and worked for different scheduled hours (SMH) on a daily basis (Table 19).

Table 19: Machine study data for GB crew (n=1)

Machine	Make	Type	Avg. power (kW)	SMH/day
Harvester	CAT 324D/325C	Harvester	140	8.5
Skidder	CAT 545C	Grapple skidder	173	11
Processor	Komatsu (PC300)	Excavator (Processing head)	126	10
Loader	CAT 938F/938G	Front-end Loader	127	11.5

This GB crew harvested a total wood volume of 190,270 cubic metres of graded logs by using a total of 271,140 litres of fuel in which the average piece size handled was 1.95 cubic metres for the 247 harvesting days worked in 2013. The operations were executed on harvesting sites with flat and rolling slopes on pumice soils with dry, moist, and wet surface conditions throughout the year. The average power and skidding distance for the crew was 142 kW and 400 metres, respectively. Fuel used by individual machine by month was derived from daily fuel supply and production data also containing total number of days worked by month. Table 20 shows crew fuel used, total production and number of days worked by month during the year 2013.

Table 20: Monthly fuel use and production data by machine for the GB crew (n=1)

Month	Days/Month	Production (m^3/month)	Fuel consumption by machine (l/month)			
			Harvester	Skidder	Processor	Loader
Jan	20	13,600	6,200	2,840	3,500	5,060
Feb	19	13,600	5,200	3,070	2,980	7,200
Mar	20	15,900	6,100	4,200	3,900	9,900
Apr	20	17,400	6,700	3,600	5,400	8,000
May	23	17,800	8,100	3,100	6,650	9,900
Jun	19	14,100	4,990	3,980	9,100	5,300
Jul	23	18,800	6,080	3,680	9,760	4,900
Aug	22	16,850	5,200	4,390	9,080	4,700
Sep	21	17,100	5,800	4,280	8,780	5,300
Oct	22	16,260	5,980	3,700	9,770	5,100
Nov	21	16,560	5,600	4,300	9,100	4,140
Dec	17	12,300	4,000	2,600	6,800	3,170
Total	***247***	***190,270***	***69,950***	***43,800***	***84,720***	***72,670***

4.2 Analysis of results

4.2.1 Average monthly rates of fuel use by logging crews and variability

All the GB crews with fuel use and production data by month showed a minimum rate of monthly fuel use of 1.29 l/m^3 and a maximum rate of use of 8.26 l/m^3 across the year 2013 (Table 21). The highest observed maximum rate of fuel use occurred in May (8.26 l/m^3) and January (7.74 l/m^3). On average, January showed the highest rate of fuel use of 4.36 l/m^3 compared to August (2.90 l/m^3), November (2.66 l/m^3) and all the other months. There was also an observed high variation of monthly rates of fuel use in May (60%) and December (54%), with the lowest variability in rates of fuel use at 34%, occurring in both March and September.

Table 21: Monthly fuel consumption and variation (%) for all GB crews combined (2013 data, n=11)

	Monthly fuel consumption (l/m^3)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	4.36	1.29	7.74	1.96	45
Feb	3.50	1.36	6.66	1.69	48
Mar	3.23	1.51	4.96	1.09	34
Apr	3.48	1.37	5.80	1.34	38
May	3.63	1.55	8.26	2.18	60
Jun	3.59	1.66	5.64	1.38	38
Jul	3.22	1.30	5.08	1.26	39
Aug	2.90	1.39	4.57	1.09	38
Sep	3.29	1.42	4.49	1.12	34
Oct	3.66	1.51	5.63	1.40	38
Nov	2.66	1.32	4.09	1.17	44
Dec	3.51	1.35	6.59	1.91	54

There were differences within and between most GB crews with respect to average monthly rates of fuel use and deviations (Figure 13). For example, GB1 logging crew had the lowest average rate of fuel use with the lowest variability compared to GB4 and GB5 crews. Simialrly GB4 and GB5 crews had the highest variability in average rates of fuel use but each with individual varying difrenecs.

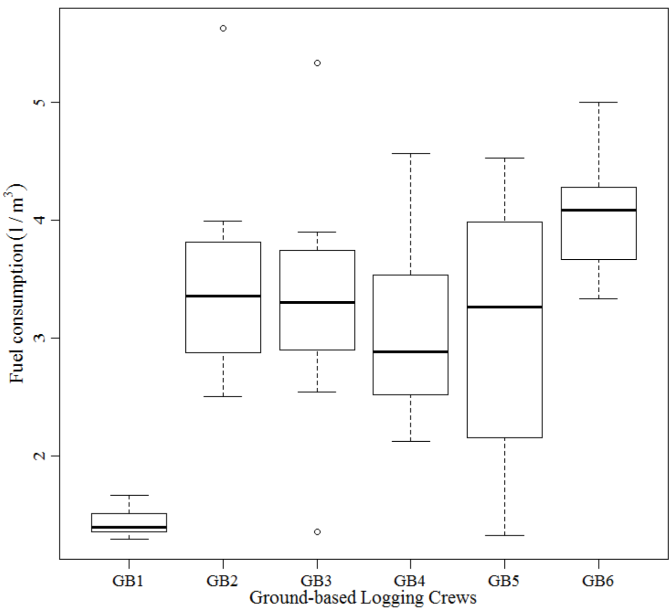

Figure 13: Box and whisker plots showing the median, 25th and 75th percentile rates of fuel use for 6 GB crews

Table 22 shows a summary of rates of fuel use for all the CY crews with monthly fuel use and production data for the year 2013 combined. The minimum monthly rate of fuel use for all the CY crews combined was 1.84 l/m^3 (May and November) while the maximum rates of fuel use were 7.03

l/m^3 (January) and 7.29 l/m^3 (December). On average all the CY crews combined used maximum rates fuel of 4.15 l/m^3 in January and a minimum of 3.00 l/m^3 in June. Rates of fuel use were highly variable in January (33%) and December (48%).

Table 22: Monthly fuel consumption and variation (%) for CY crews combined (2013 data, n=12)

	Monthly fuel consumption (l/m^3)				
Month	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Jan	4.15	2.47	7.03	1.36	33
Feb	3.25	2.57	4.24	0.56	17
Mar	3.16	2.12	4.26	0.83	26
Apr	3.14	2.13	4.28	0.65	21
May	3.16	1.84	3.98	0.65	21
Jun	3.00	1.96	4.41	0.76	25
Jul	3.13	2.18	4.67	0.73	23
Aug	3.26	2.33	5.06	0.73	23
Sep	3.07	2.19	3.80	0.60	20
Oct	3.04	2.09	3.60	0.55	18
Nov	3.04	1.84	4.40	0.85	28
Dec	3.30	2.01	7.29	1.60	48

For 2014 CY crew monthly data (n=3), the average rates of fuel use ranged from a minimum of 2.26 l/m^3 to a maximum of 4.43 l/m^3. The lowest and maximum average rates of fuel use for all the three CY crews occurred in December and January, respectively. Notably, variations in rates of use were high in June (46%) and December (44%) for the all CY systems in 2014 data. For all the CY crews with monthly data in the study data (n=9), there were observed differences in variability on average fuel consumption rates across the year (Figure 14). For example, CY2 and CY7 had different average rates of fuel use and also the lowest variability within and between them compared to the all the other CY crews with monthly data.

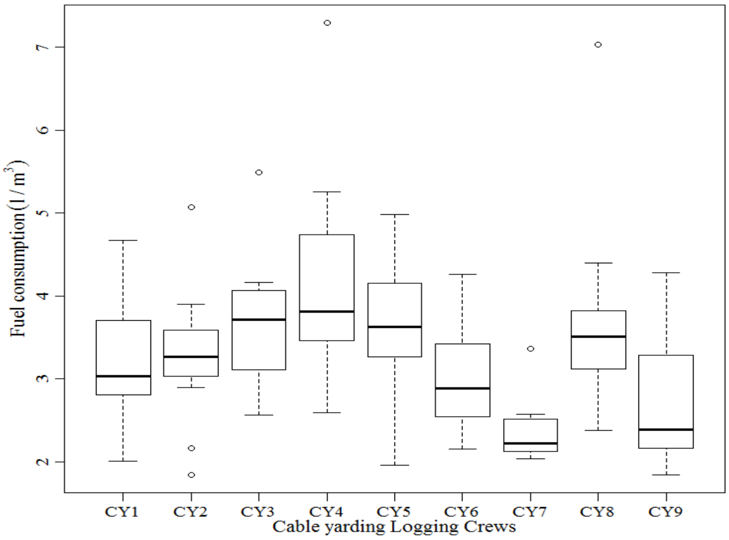

Figure 14: Box and whisker plots showing the median, 25th and 75th percentile rates of fuel use for 9 CY crews

4.2.2 Rates of fuel use by harvesting system

Rates of fuel use in l/m³

From the summary of all study data (see Table 16), based on total gross volumes of timber harvested and fuel used for the entire period of study data, the weighted average rate of fuel use for all GB harvesting systems was 2.66 l/m^3 while that of CY harvesting systems was 3.16 l/m^3. However, the average system rate of fuel use for all 17 ground-based harvesting systems combined was 3.04 l/m^3 and 3.18 l/m^3 for all 28 CY harvesting systems combined. The rates of fuel use for GB systems were more variable (31%) and ranging from 1.43 to 5.41 l/m^3, compared to those of CY systems The variability in average rates of fuel use for all the GB harvesting systems was associated with differences in felling and processing mechanisation, whether a crew had stemming or non-stemming operations, and differences in site characteristics and extraction distances. There was 12% variability in average rates of fuel use by CY harvesting systems with rates of fuel use ranging from 2.35 to 3.98 l/m^3. This variability in average rates of fuel use by CY systems was attributed to differences in rigging configurations, number of machines used and level of mechanisation. These results indicate that on average, GB systems are the most fuel efficient harvesting systems compared to CY. All the combined study data (n=45) showed a variation of 21% in average rates of fuel use.

Paired t-tests showed that average rates of fuel use between GB and CY harvesting systems were not significantly different (p-value=0.59). Further statistical tests of significance also showed no significant relationship between rates of fuel use in l/m^3 and type of harvesting system (p-value=0.51). This implied that the null hypothesis, that GB and CY harvesting systems use fuel in l/m^3 at the same rates during harvesting irrespective of machine selection, was accepted at 95% level of confidence, as the two harvesting systems use equal rates of fuel based on the data analysed, regardless of prevailing harvesting site factors and machines involved. From this point on, the average rate of fuel use for this study is taken as 3.04 l/m^3 and 3.18 l/m^3 for GB and CY harvesting systems respectively; as they represent all the study data by year of harvesting and average rates of fuel use for all the combined logging crews. Further analyses are based on all study data from which these average rates of use by GB and CY harvesting systems have been derived. Table 23 shows a summary of rates of fuel use for GB and CY harvesting systems and standard deviation (SD) under harvesting conditions specific to New Zealand.

Table 23: Summary of rates of fuel use in l/m^3 by harvesting systems (n=45)

	Fuel consumption (l/m^3)				
System	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
GB	3.04	1.43	5.41	0.95	31
CY	3.18	2.35	3.98	0.39	12
Combined	3.13	1.43	5.41	0.65	21

Rates of fuel use in l/kWhr

On average, all GB logging systems combined used 0.15 l/kWhr compared to 0.09 l/kWhr used by CY harvesting systems. Rates of fuel use in l/kWhr by GB systems ranged from 0.10 to 0.23 l/kWhr while those of CY systems ranged from 0.05 l/kWhr to 0.13 l/kWhr. These ranges in rates of fuel use in l/kWhr showed more variability (31%) for CY harvesting systems compared to variations in rates of fuel use by GB harvesting systems (25%). Combined data for the study shows that rates of use are generally more variable (38%). Paired t-tests showed that average rates of fuel use in l/kWhr between GB and CY harvesting systems were significantly different (p-value<0.0001). ANOVA tests further showed that rates of fuel use in l/kWhr were significantly diffrent with the type of harvesting system (p-value <0.0001). Therefore, the null hypothesis that rates of fuel use in l/kWhr between GB and CY harvesting systems are similar irrespective of machines selected was rejected at 95% test level of confidence. The results of rates of fuel use of 0.15 l/kWhr and 0.09 l/kWhr for GB and CY harvesting systems respectively have been taken as the benchmark for the study. Table 24 shows the summary of rates of fuel use in l/kWhr for GB, CY and combined harvesting systems.

Table 24: Summary of rates of fuel use in l/kWhr by harvesting systems (n=45)

System	Fuel consumption (l/kWhr) Average	Minimum	Maximum	SD	Variation (%)
GB	0.15	0.1	0.23	0.04	25
CY	0.09	0.05	0.13	0.03	31
Combined	0.12	0.05	0.23	0.04	38

4.2.3 Harvesting site characteristics and rates of fuel use

Rates of fuel use and slope

The average rate of fuel use on flat slope harvest site was 2.22 l/m^3 and ranged between 1.43 l/m^3 and 2.91 l/m^3. Rates of fuel use on rolling slopes were higher (3.39 l/m^3) and more variable (2.34 to 5.41 l/m^3) than those on flat slopes. These rates of fuel use on flat and rolling slope harvesting sites were all associated with GB harvesting operations; no CY systems operated on these slopes. The variability in rates of fuel use on flat and rolling harvest sites could be attributed to differences in average extraction distances and resistances due to gravitational pull associated when pulling uphill against the rolling slopes. Variability on rates of fuel use on flat and rolling slopes were also attributed to resistances associated with skidding branched versus delimbed stems, differences in the magnitudes of frictional forces acting on skidder tyres and dragged stems with the ground and maximum allowable payloads.

The average rate of fuel use on steep slope harvesting sites was 3.18 l/m^3 and varied from 2.35 to 3.98 l/m^3. These average rates of fuel use on steep slopes were associated with all CY harvesting operations; no GB systems operated on steep slopes. The rates of fuel use on steep slopes were also lower compared to the rates of fuel use on rolling slopes mainly by GB systems. Rates of fuel use on rolling and steep slopes do not show clear variability between them but show a clear difference in variability, unlike with rates of fuel use on flat slopes (Figure 15). ANOVA showed that rates of fuel use in l/m^3 are dependent on slope (p-value=0.002). The significant differences in rates of fuel use shown by ANOVA are attributed to variations in slope percent and differences in skidding by GB systems versus yarding by CY systems as noted by Visser and Stampfer (1998). Moreover, skidding involves pulling or dragging of stems that are constantly in contact with the ground while cable yarding configurations involve skyline suspensions with logs wholly or partially suspended from the ground. ANCOVA tests showed that rates of fuel use in l/m^3 are only significantly different with rolling slopes (p-value =0.0004) and steep slopes (p-value =0.01).

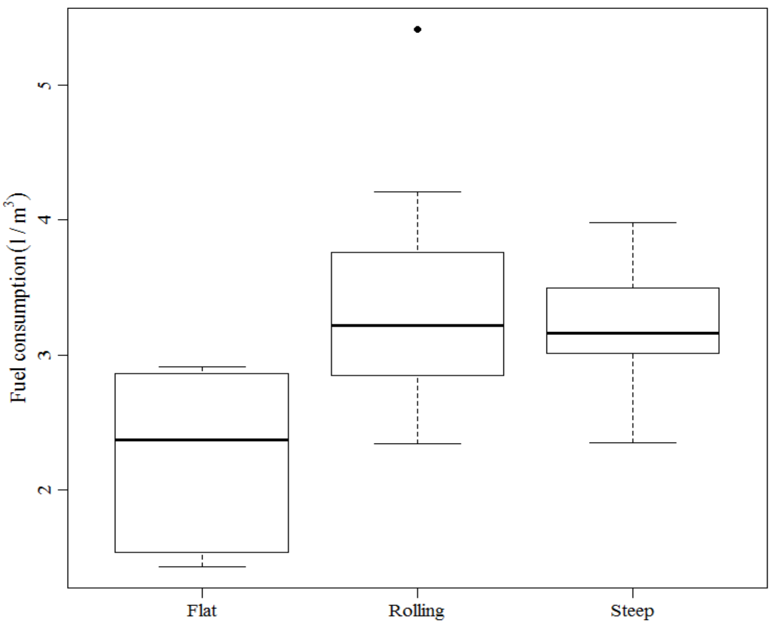

Figure 15: Box and whisker plots showing rates of fuel use in l/m^3 by slope category

The rate of fuel use in l/kWhr on flat slopes was 0.15 l/kWhr and ranged from 0.11 to 0.18 l/kWhr in comparison with rates of use on rollling slopes with an average of 0.16 l/kWhr and varied from 0.10 to 0.23 l/kWhr. The rates of fuel use in l/kWhr on both flat and rolling slopes were associated with only GB operations since all the CY operations were conducted on steep slopes. The higher rates of use on rollling harvest sites were associated with more power being drawn by skidders to overcome the negative effect of gravity due to adverse gradient. The average rate of fuel use on steep slopes was 0.09 l/kWhr and ranged from 0.05 to 0.13 l/kWhr. The rates of fuel use in l/kWhr on steep slopes are associted with only CY opertions and were much lower and less variable compared to rates reported on flat and rolling slopes for GB operations. The range of rates of fuel use on flat slopes occurred within the rates of use on rolling slopes, however, variability on rates of use on steep slopes was distinct from rates of use on flat and rolling slopes (Figure 16). ANOVA showed that rates of fuel use in l/kWhr are highly depeneddnt on slope (p-value <0.0001). ANCOVA tests further showed that rates of fuel use in l/kWhr were significantly different with steep slopes (p-value=0.04) but insignificant with rolling slopes (p-value=0.31).

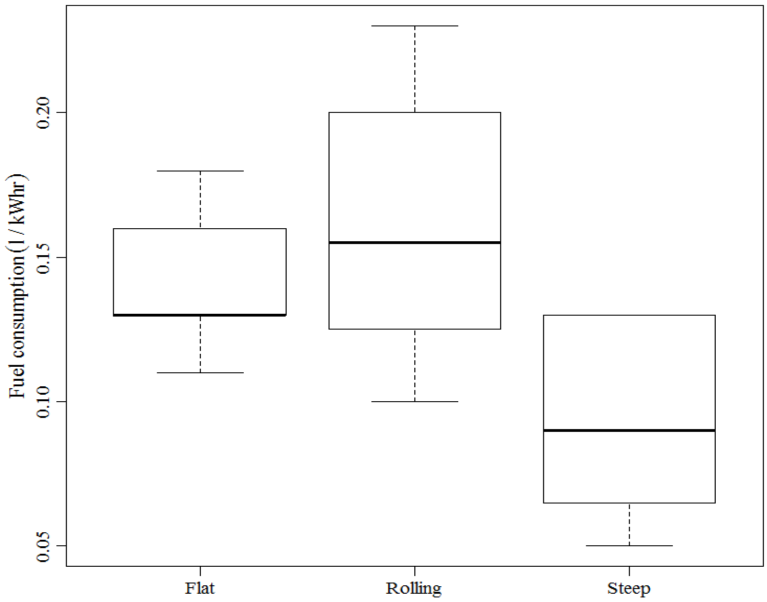

Figure 16: Box and whisker plots showing rates of fuel use in l/kwhr by slope category

Rates of fuel use and direction of pulling

The average rate of fuel use during harvesting when pulling on typically flat sites was 2.53 l/m^3 and ranged from 1.43 to 4.04 l/m^3. Average rate of fuel use during harvesting when pulling towards variable directions during extraction was 3.49 l/m^3 and ranged from 2.90 to 4.21 l/m^3. Pulling on flat ground towards variable directions was associated only with GB harvesting systems. Pulling in variable directions was however, assumed towards any direction and not specific to flat or uphill directions by data providers. The average rate of fuel use when pulling uphill was 3.19 l/m^3 and varied from 2.34 to 5.41 l/m^3. Data for pulling uphill came from both steep slope CY and rolling slope skidding operations from GB systems. However, most of the data was associated with CY steep slope operations. The rates of fuel use when pulling on flat sites was more variable compared those of variable and uphill directions of pulling (Figure 17). ANOVA tests at 95% level of confidence showed that rates of fuel use in l/m^3 were significantly different with direction of pulling (p-value=0.03). ANCOVA tests further showed that rates of fuel use in l/m^3 were also significantly diffrent with both uphill (p-value=0.02) and variable directions of pulling (p-value=0.02). The variability of rates of use associated with directions of pulling was attributed to differences in maximum payloads by cable yarder and skidder machines coupled with changing average extraction distances, and the effects of gravitational resistances due to adverse gradients.

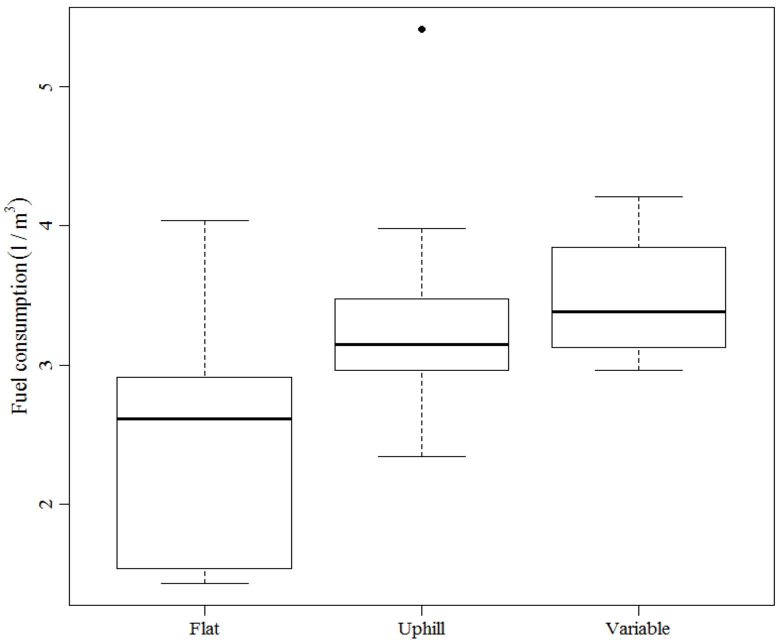

Figure 17: Box and whisker plots showing rates of fuel use in l/m^3 by direction of pulling during extraction

The average rate of fuel use in l/kWhr for pulling on flat harvesting site was 0.15 l/kWhr with a range from 0.11 to 0.21 l/kWhr. These rates are indicators of very intensive skidder operations on flat harvesting as engines draw more fuel per unit of power. The average rate of fuel use for pulling uphill was 0.11 l/kWhr and was more variable (0.05 - 0.23 l/kWhr) compared to rates used when pulling on flat sites. Average rate of fuel use associated with variable directions of pulling for GB operations was 0.13 l/kWhr and ranged from 0.10 to 0.16 l/kWhr. Rates of fuel use for pulling on variable directions showed least variability compared to those on flat and uphill pulling. Pulling on flat and variable directions were exclusively by GB harvesting systems while uphill pulling was associated with both GB and CY harvestings systems, with most data coming from CY operations.

The variability in average rates of fuel use in l/kWhr (Figure 18) could be attributed to variations in average power rating between skidders and cable yarding machines, slope in percent incline, maximum payloads and differences in extraction distances. For example, cable yarding systems with shotgunning configuration require fuel only during the inhaul. Alternatively, during the outhaul, the carriage is aided by force of gravity and does not require fuel. Skidders operating on flat and variable harvest sites were also assumed to engage engines during both outhaul and inhaul, thus drawing more power during the whole cycle compared to CY shotgunning. However, the survey could not verify the rates of fuel use between various cable yarding configurations used by each crew as this data was not provided. ANOVA tests at 95% level of confidence showed that rates of fuel use in l/kWhr were significantly diffrent with direction of pulling (p-value=0.03). However, ANCOVA tests indicated that these rates of fuel use in l/kWhr were only significantly diffrent with uphill direction of pulling (p-value=0.02).

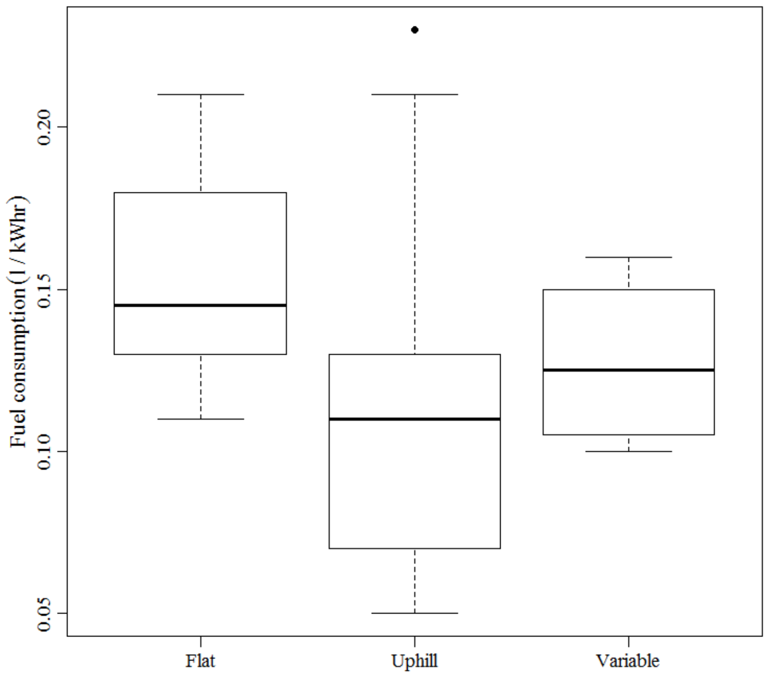

Figure 18: Box and whisker plots showing rates of fuel use in l/kWhr by direction of pulling during extraction

Rates of fuel use and surface moisture conditions

Rates of fuel use were higher for operations conducted on harvest sites with wet and moist/wet surface moisture conditions, in comparison to rates of use on dry and moist surface conditions. The average rates of fuel use for operations on wet surface conditions was 3.40 l/m^3, moist/wet 3.15 l/m^3, moist 3.11 l/m^3, dry/moist 2.87 l/m^3, dry conditions 2.67 l/m^3, and variable moisture conditions was 3.10l/m^3. These results show high variability for rates of use on dry/moist and low variability for rates of use on wet surface conditions compared to moist, moist/wet and variable surface moisture conditions during harvesting (Figure 19).

ANOVA tests at 95% level of confidence showed that rates of fuel use in l/m^3 were not significantly different with surface moisture conditions (p-value=0.74). ANCOVA tests further showed that rates of fuel use in l/m^3 were not significantly different with different levels of surface moisture conditions; dry/moist (p-value=0.72), moist (p-value=0.69), moist/wet (p-value=0.70), wet (p-value=0.73) and variable (p-value=0.71). Machine operations appear to be maximised during dry/moist conditions resulting in more variability in rates of use as more production is maximised to cushion economic loss associated with wet seasons. As production operations are assumed to be hampered by wet conditions, more intensive use of machines targeting more production was associated with higher fuel supply and use. Moreover, poor traction ability by the machines during the wet season results in more fuel use on non-production operations such as pulling machines stuck out of muddy conditions.

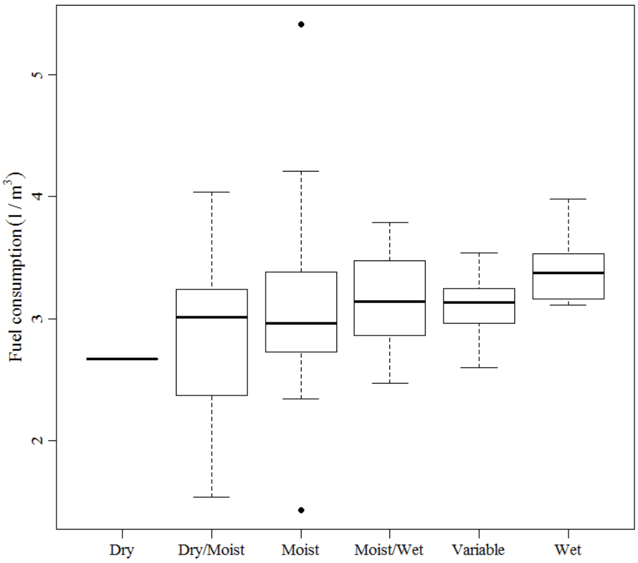

Figure 19: Box and whisker plots showing rates of fuel use by surface moisture conditions of the harvest site

The average rate of fuel use in l/kWhr for moist surface conditions was 0.14 l/kWhr and was higher compared to dry/moist and moist/wet both of which used an average of 0.12 l/kWhr. The lowest rates of use in l/kWhr were equal for variable and wet conditions at 0.09 l/kWhr. There was more machine engagement during dry, dry/moist, and wet/moist conditions, based on these rates of fuel use. On purely wet conditions, most crews tended to minimise production operations to mitigate losses associated with low production. ANOVA tests at 95% level of confidence showed that rate of fuel use in l/kWhr was significantly diffrent with surface moisture conditions (p-value=0.01). However, ANCOVA tests showed indicated that no single level of surface moisture condition had a significant effect on rates of fuel use; dry/moist (p-value=0.28), moist (p-value=0.08), moist/wet (p-value=0.20), wet (p-value=0.71) and variable (p-value=0.72). These rates of fuel use in l/kWhr subject to surface moisture conditions were not harvesting system specific as both GB and CY operations were conducted under all moisture conditions.

4.2.4 Rates of fuel use and harvesting seasons

The average rates of fuel use were higher at the start of the year (January) and tended to be low at the close of operations in December. Rates of fuel use for both GB and CY harvesting systems also appeared stable with minimal variations between February and May, but showed variation towards the onset of winter between May and June onwards to the end of October (Figure 20). During summer months (October to December), more production operations were executed with more fuel supplies, use, and variability for most GB operations, unlike rates of fuel use associated with CY operations that remained fairly stable from February through the end of the year. The previous sections on system rates of fuel use showed that rates of fuel use in l/m^3 for GB were more variable (31%) than those of CY (12%) across the year (see Table 23).

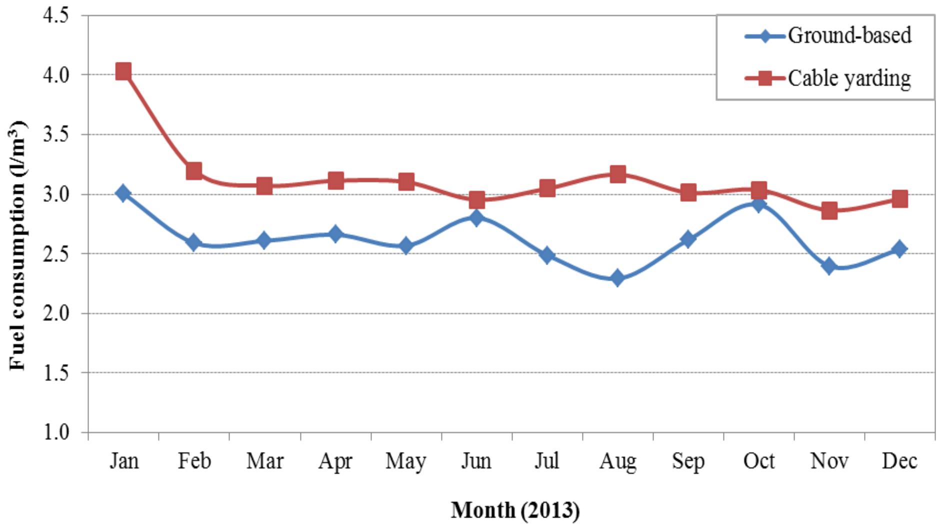

Figure 20: Trends for average monthly fuel consumption rates between GB and CY harvesting systems for 2013 compared

The annual and monthly fuel consumption rates for CY harvesting systems comparing 2013 and 2014 data (Figure 21) depicted differences in harvesting scenarios that could be associated with varying annual climatic patterns, crews operating on new harvesting sites under varying slopes, and stand attributes.

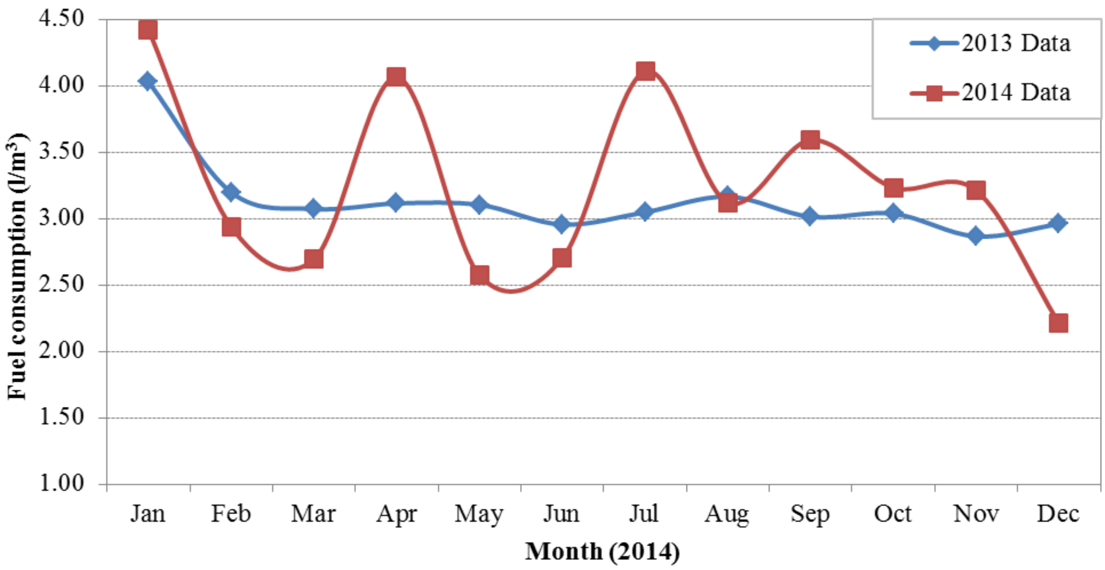

Figure 21: Trends for average monthly fuel consumption rates by CY harvesting systems for year 2013 and 2014 compared

4.2.5 Mechanisation and rates of fuel use

Rates of fuel use also depended on levels of mechanisation by GB and CY harvesting operations. Fully manual GB operation used the highest average rate of fuel of 3.40 l/m^3 compared to that of fully mechanised GB operation whose rate of fuel use was 2.47 l/m^3. Mechanised GB operations produced more harvesting volumes compared to similar manual GB harvesting operations. Consumption rates by manual GB, manual CY and fully mechanised CY were higher than the rates reported by Sandilands et al. (2009), Karalus (2010), Amishev (2010) and Dash and Marshall (2011), with the exception of mechanised GB in this study that showed lower rates compared to the results of previous studies in New Zealand. High fuel consumption rates associated with fully manual GB harvesting operations could explain its low presence in New Zealand. The differences in average rates of fuel use between manual and mechanised CY systems were however, marginal compared to that between manual and mechanised GB systems. Summary of average fuel consumption for the various manual and mechanised systems are shown in Table 25.

Table 25: Summary of fuel use rates by types of harvesting system mechanisation (n=45)

	Average fuel use rates	
Type of harvesting system	l/m^3	l/khwr
Manual Ground-based	3.40	0.18
Mechanised Ground-based	2.47	0.14
Manual Cable logging	3.24	0.13
Mechanised Cable logging	3.35	0.11
Manual felling + mechanised processing (Ground-based)	2.61	0.16
Manual felling + mechanised processing (Cable logging)	3.12	0.09
Mechanised felling + manual processing (Cable logging)	3.25	0.05

4.2.6 Rates of fuel use by machines

Average, minimum and maximum monthly fuel use rates in l/m^3, l/kWhr and l/SMH by machines were determined (Table 26) based on daily data on SMH and fuel supply, number of days worked and monthly total crew production. Skidders used the lowest average rate of fuel use (and range) of 0.23 l/m^3 (0.17 to 0.28 l/m^3). Processor machines used the highest rates of fuel use (and range) of 0.44 l/m^3 (0.22 to 0.67 l/m^3). Both processers and loaders showed equal variability in average rates of fuel use for the GB crew surveyed.

Table 26: Fuel use rates (l/m^3) by GB machines (n=1)

Machine	Fuel consumption (l/m^3)				Variation (%)
	Average	Minimum	Maximum	SD	
Harvester	0.37	0.31	0.46	0.05	13
Skidder	0.23	0.17	0.28	0.03	14
Processor	0.44	0.22	0.64	0.15	34
Loader	0.38	0.25	0.62	0.13	34

The average rates of fuel by machines in l/kWhr showed similar patterns with skidders having the lowest average rate of use of 0.09 l/kWhr and processor machine the highest rate of 0.27 l/kWhr (Table 27). Processers and loaders showed higher and almost similar variation in average rates of fuel use compared to variation in rates of use shown by both harvesters and skidders.

Table 27: Fuel use rates (l/kWhr) by GB machines (n=1)

Machine	Fuel consumption (l/kWhr)				Variation (%)
	Average	Minimum	Maximum	SD	
Harvester	0.24	0.2	0.3	0.03	13
Skidder	0.09	0.07	0.11	0.01	16
Processor	0.27	0.12	0.38	0.09	34
Loader	0.22	0.14	0.37	0.08	35

Rates of fuel use per SMH showed that processor machines had the highest rates of use followed by loaders, harvesters with skidders having the least rates of fuel use (Table 28). The differences in variability on rates of fuel use between processor and loader machines were however, marginal.

Table 28: Fuel use rates (l/SMH) by GB machines (n=1)

Machine	Fuel consumption (l/SMH)				Variation (%)
	Average	Minimum	Maximum	SD	
Harvester	33.23	27.73	41.55	4.27	13
Skidder	16.14	12.21	19.15	2.52	16
Processor	34.11	15.71	47.78	11.69	34
Loader	28.02	17.77	46.92	9.87	35

Skidders were the most fuel efficient of all the GB machines analysed from the data provided by the mechanised GB crew, while loaders and harvesters used almost similar quantities of fuel per unit of production, suggesting that skidders remain the most fuel efficient machines for ground-based operations. Processors showed the highest average rate of fuel use per unit of production. Since processor productivity has been shown to be dependent on material availability and piece size handled (Tolan & Visser, 2015; Visser & Spinelli, 2012), the number of times the processor handles any given stem when converting it to a merchantable log grade could explain the high variability in rates of fuel use during operations. Given similar average power ratings between the processor and front-end loaders, the high rate of fuel consumptions of 34.2l/SMH by the processor in comparison to that of loaders (28.02l/SMH) is an indication that processors handle more stems during processing compared to loading machines. Productivity of loading machines depended on processor output as most loading machines appear to handle graded during stacking, fleeting, and storage within the landing, but this productivity of loaders change for a two-staging operation involving off-loading of stem trucks. For the fully mechanised GB crew, a total of 112 litres of fuel was used for hourly production. The average rates of fuel consumption in l/m^3 by these machines could be used as an indicator of variable rates of fuel between phases of harvesting (Figure 22).

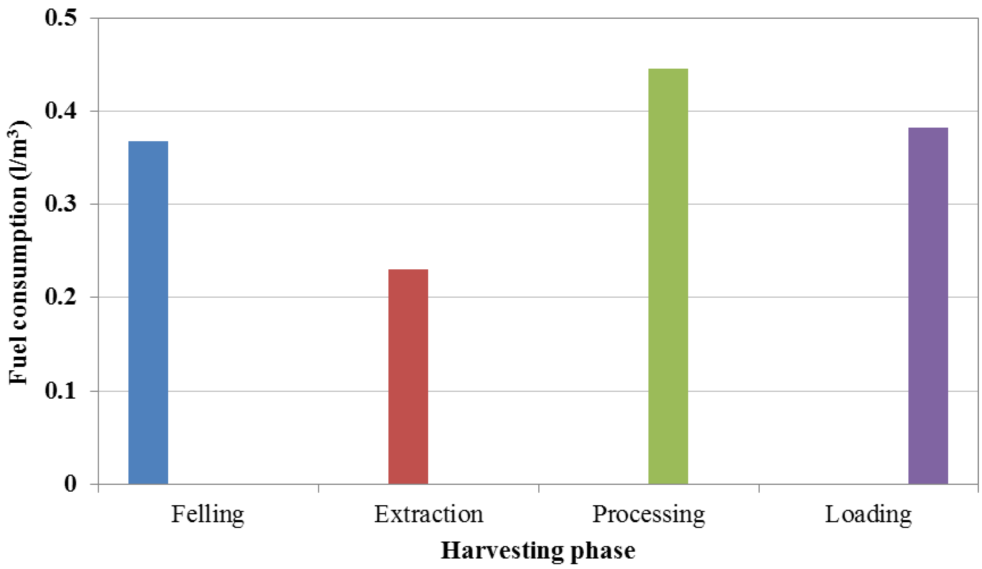

Figure 22: Rates of fuel use by phase of harvesting

4.3 Summary results for the Southern US Ground-based crews

Data used in the Southern US state fuel use study was provided by different number of logging crews: Alabama (7), Ohio (5), 2 crews each from Florida and North Carolina, and one crew each from Georgia and Louisiana. All the 18 GB crews from the Southern US harvested a combined total volume of 1,380,200 cubic metres (metric tonnes) of wood using approximately 2,791,100 litres of fuel on annual scale, giving a weighted fuel use rate of 2.02 l/m^3 for the region. For the combined study data for the 18 crews, the minimum annual average production rate by a single crew was 30,300 m^3 and a maximum of 118,200 m^3. A single crew also used a minimum of 46,880 litres and a maximum of 340,800 litres of fuel annually. The average rate of fuel use for all the 18 crews combined was 1.99 l/m^3 and varied from 1.26 to 3.63 l/m^3. This average rate of fuel use of 1.99 l/m^3 was taken as the benchmark for all the Southern US GB crews for comparative purposes with New Zealand GB crews.

The average rate of fuel use for the GB crews operating on clear-cutting operations was 2.06 l/m^3, which was higher and more variable (36%) than thinning crews whose average rate of fuel use was 1.88 l/m^3 with a variability of 17%. However, the rates of fuel use for single crews performing both thinning and clear-cutting operations showed that thinning operations used higher rates of fuel than clear-cutting operations. For example the average rate of fuel use by four combined Alabama crews with both thinning and clear-cutting operations was 1.75 l/m^3 compared to clear-cutting operations performed by the same crews with an average rate of fuel use of 1.69 l/m^3. The average rate of fuel use for thinning operations by all the Florida crews combined was 1.76 l/m^3 compared to clear-cutting operations by the same Florida crews that used fuel at an average rate of 1.65 l/m^3. Table 29 shows average rates of fuel use for thinning and clear-cutting operations by all the Southern US GB crews combined.

Table 29: Rates of fuel use by type of cut and system for South US GB crews (n=18)

	Rates of fuel consumption (l/m^3)				
System	**Average**	**Minimum**	**Maximum**	**SD**	**Variation (%)**
Thinning	1.88	1.44	2.55	0.32	17
Clear-cutting	2.06	1.26	3.63	0.75	36
Combined System	1.99	1.26	3.63	0.62	31

Harvesting site conditions and factors associated with the Southern US fuel use data

The Southern US data had no specifications on average extraction distances and directions of pulling during extraction associated with crew. The various categories of harvesting sites were however, defined with four categories of slopes; flat (0% slope), rolling (0-15% slope), steep (0-34% slope), and very steep (>35% slope). Based on slope categories, of the 7 Alabama crews, 3 worked on typically flat slopes, 2 worked on both flat and rolling slopes, and the remaining 3 on sites with variable slopes (flat, rolling and steep slopes). Florida and North Carolina crews all worked on flat slopes, Georgia and Louisiana crews on rolling slopes and all Ohio crews worked on steep slopes. There was limited data regarding soil moisture conditions for crews from Alabama and Florida states. Data on surface soil moisture conditions at the time of harvesting indicated that only three Alabama and Florida crews worked on dry, moist and wet soil moisture conditions, North Carolina on wet soils conditions, while all the remaining Alabama, Louisianan, Georgia, and Ohio crews did not specify any information on soil moisture conditions of the harvest sites for the period captured by the survey data.

4.4 Comparisons of rates of fuel use

a) Harvesting systems rates of fuel use (study) and rates of use in literature compared

Results from this study show that the rates of fuel use by GB and CY harvesting systems operating under harvesting conditions of New Zealand are higher than those reported by Sambo (2002), Smidt and Gallagher (2013), Greene et al. (2014) and Baker and Greene (2012) (Table 30). Rates of fuel use for clear felling operations by GB crews in New Zealand are also higher than rates used in thinning operations as conducted by Sambo (2002) and those of Smidt and Gallagher (2013).

Table 30: Rates of fuel use for the study (bold and italic) and data in literature compared

	Fuel use rates (l/m^3)		
Author (year)	***Thinning***	***Clear-cutting***	***System average***
NZ Study (Ground-based)	-	***3.04***	***3.04***
NZ Study (Cable yarding)	-	***3.18***	***3.18***
Sambo (2002)	2.66	1.99	2.32
Smidt & Gallagher (2013)	2.32	1.92	2.12
Green & Biang (2014)	-	-	2.43

b) Rates of fuel use by New Zealand and South US Ground-based crews compared

Results of the study show that on average all New Zealand GB crews combined use 3.04 l/m^3 while GB crews of the Southern US combined use 1.99 l/m^3. Rates of fuel use by New Zealand GB crews are also more variable (1.43 to 5.41 l/m^3) compared to average rates of Southern US GB crews combined (1.26 to 3.63 l/m^3) as in Figure 23. In proportion, the average rate of fuel use by all the GB crews in New Zealand combined is 32% higher than those of similar GB crews in the Southern US. New Zealand GB crews also use more fuel on average for clear-felling operations compared to rates used for thinning and clear felling operations by similar Southern US GB crews. Paired t-tests showed that the average rates of fuel use by New Zealand and Southern US were significantly different (p-value=0.002). The differences in the average rates of fuel use between the two countries was attributed to variations in slope, directions of pull, number of machines used, number of log products produced and intrinsic properties of harvested species. Most crews in Southern US states also operated on flat slopes, used fewer machines, and produced mostly three log grades of pulp, plus saw and structural logs. Comparatively, GB crews in New Zealand operated on varying degrees of flat and rolling slopes, and were skidding logs/stems towards various directions during extraction as well as producing greater number of log grades.

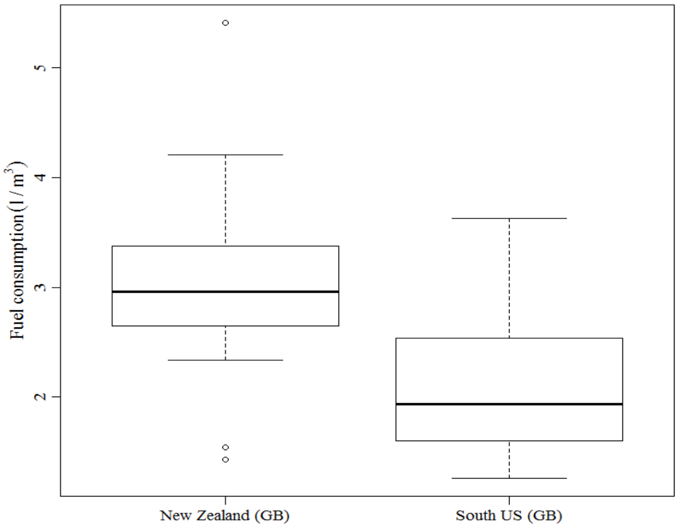

Figure 23: Box and whisker plots showing the median, 25th and 75th percentiles, and interquartile range of fuel consumption by New Zealand and Southern US GB systems

New Zealand and Southern US states generally experience similar weather conditions across the year, but at opposite hemispheres, making rates of fuel use for similar months difficult to compare (Figure 24) due to the alternating climatic seasons. For example, winter period in New Zealand occurs corresponds to summer months in the Southern US. More logging operations are usually conducted during summer months in the Southern US states due to dry harvesting site conditions whereas logging crews in New Zealand usually slow down operations about the same time of the year due to wet harvest site conditions.

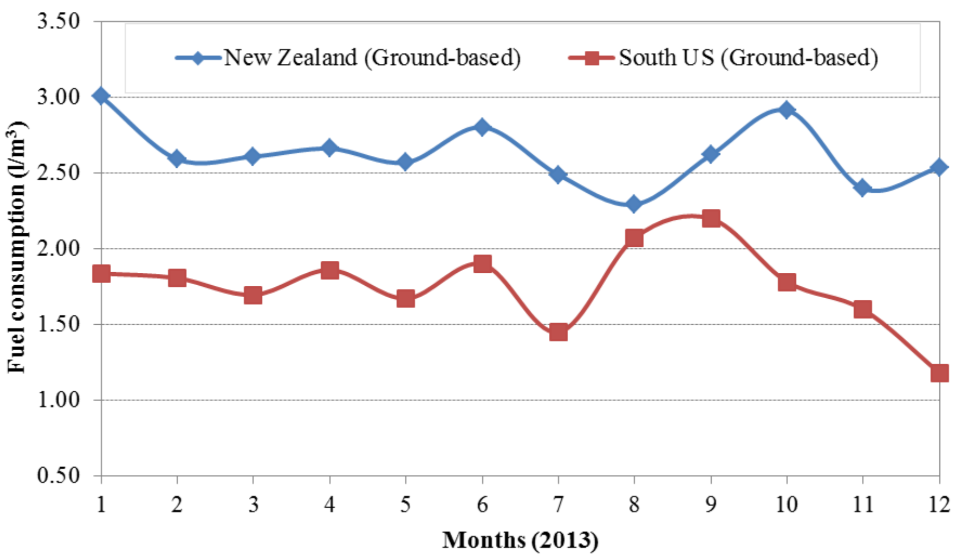

Figure 24: Trends of fuel use rates for New Zealand and South US states combined

c) Rates of fuel use by machines (study data) and INFORME 2013 machine data compared

Annual published INFORME Consulting machine data was used to derive machine fuel use rates in l/kWhr and l/SMH, but not in l/m^3, as there was no data on machine productivity (FORME, 2012). The publication also does not indicate harvesting site factors associated with individual machine during harvesting. Study results show that harvesters use 0.24 l/kWhr compared to 0.20 l/kWhr determined from FORME (2012) data. The study results also showed that processors used an average of 0.27 l/kWhr which is higher than 0.20 l/kWhr by FORME (2012) processors. Skidders in the study use 0.09 l/kWhr which are lower than FORME (2012) skidders whose rates of use range from 0.13 to 0.14 l/kWhr. However, front end-loaders in the study used similar rates of fuel as those derived using FORME (2012) fuel data. The rates of fuel use determined from FORME (2012) data were based on standard operations of 8 SMH and 175 days annually, compared to machines in the study with varying SMH and days annually. There were also variations in rates of power between similar types of machines in the study and those of FORME (2012) as shown in Table 31.

Table 31: Machine fuel use rates for study data (bold italic) and FORME (2013) data compared

Machine	Avg. Power (kW)	SMH	Days/Year	l/SMH	l/kWhr
Feller-buncher/Harvester	200	8	175	40.86	0.20
Harvester (Study)	***140***	***8.5***	***247***	***33.32***	***0.24***
Grapple Skidder	125	8	175	16.89	0.14
Grapple Skidder	150	8	175	18.87	0.13
Grapple Skidder (Study)	***173***	***11***	***247***	***16.12***	***0.09***
Excavator Processor	104	8	175	20.50	0.20
Excavator Processor	200	8	175	39.86	0.20
Excavator Processor (Study)	***126***	***10***	***247***	***34.20***	***0.27***
Front-end Loader	110	8	175	12.51	0.11
Front-end Loader	155	8	175	17.51	0.11
Front-end Loader (Study)	***127***	***10***	***247***	***14.01***	***0.11***

d) Machine rates from study and rates in literature review compared

Data presented in the literature indicated that a harvester uses 0.09 l/kWhr (Holzleitner et al., 2011) which is lower compared to 0.24 l/kWhr used by harvesters in the study. However, harvesters in the study used an average of 0.37 l/m^3 which is lower compared to rates of fuel used by harvesters performing similar operations in Smidt and Gallagher (2013) studies, and harvester fuel rates by Baker and Greene (2012) for similar operations. The harvesters in the study used an average of 33.2

l/SMH which also compared closely with harvesters reported by Makkonen (2004). Grapple skidders in the study used 0.23 l/m^3 which is much lower compared to rates of use per unit volume of harvested wood reported by Smidt and Gallagher (2013) and skidder rates reported by Baker and Greene (2012). Similarly, skidders in the study also used lower rates of fuel in l/kWhr compared to skidders rates in l/kWhr reported by Holzleitner et al. (2011). Processors in the study used less fuel per unit of production compared to processors in Smidt and Gallagher (2013) studies. However, the same processors used considerably more fuel per SMH than processor rates reported by Makkonen (2004). Loaders in the study used almost the same rates of fuel in l/m^3 in comparison to those of Smidt and Gallagher (2013), but their rates were much lower compared to fuel used by loaders reported in Greene et al. (2014) studies. Table 32 presents summary of fuel use rates in l/m^3, l/kWhr, and l/SMH for all the survey data as compared to the rates reported by selected authors who studied and reported rates of fuel use for similar machines.

Table 32: Fuel use rates by machines in the study (bold italic) and literature data compared

Machine	Units	*Study*	Holzleitner et al. (2011)	Smidt & Gallagher (2013)	Green & Biang (2014)	Makkonen (2004)
Harvester	*l/m^3*	***0.37***	-	0.70	0.97	-
	l/kwhr	***0.24***	0.09	-	-	-
	l/SMH	***33.20***	-	-	-	35
Grapple skidder	*l/m^3*	***0.23***	-	0.74	0.87	-
	l/kwhr	***0.09***	0.1	-	-	-
Processor	*l/m^3*	***0.45***	-	0.68	-	-
	l/SMH	***34.20***	-	-	-	25
Loader	*l/m^3*	***0.38***	-	0.37	0.56	-

4.5 Fuel consumption relationships

Average rates of fuel use and production for both GB and CY harvesting systems were combined and analysed for linear relationships. Simple linear and power functions were used to examine linear relationships between the continuous response variables (rates of fuel use in l/m^3 and l/kWhr) and each of the predictor variables: total annual production, average piece size, number of machines used, average power rating for the system, and average extraction distances. Linear and power function relationships were preferred due to their mono-directional explanatory effect unlike quadratic functions that tend to balance linear outputs in equal decreasing and increasing proportions based on the order of polynomial functions (Visser & Spinelli, 2012).

A power function relationship between rate of fuel use in l/m^3 and total annual production showed a decreasing correlation between rate of fuel use and production (R^2=0.45). This implied that logging crews need to focus on higher production volumes as average fuel consumption rates tend to decrease with increased harvesting production. The linear relationships between rates of fuel use in l/m^3 and number of machines used, average power, and average extraction distances suggested that rates of fuel use reduces with more machines; increases with larger piece sizes handled, and also increases with increase in average extraction distances (Figure 25). There was however, a weak correlation between rates of fuel use in l/m^3 and number of machines used (R^2=0.03), average piece size (R^2=0.03), average power rating (R^2=0.03) and average extraction distances (R^2=0.06). ANOVA tests at 95% level of confidence (α=0.05) showed that rates of fuel use are not significantly different with number of machines used (p-value=0.12), average piece size (p-value=0.25), and average extraction distances (p-value=0.12).

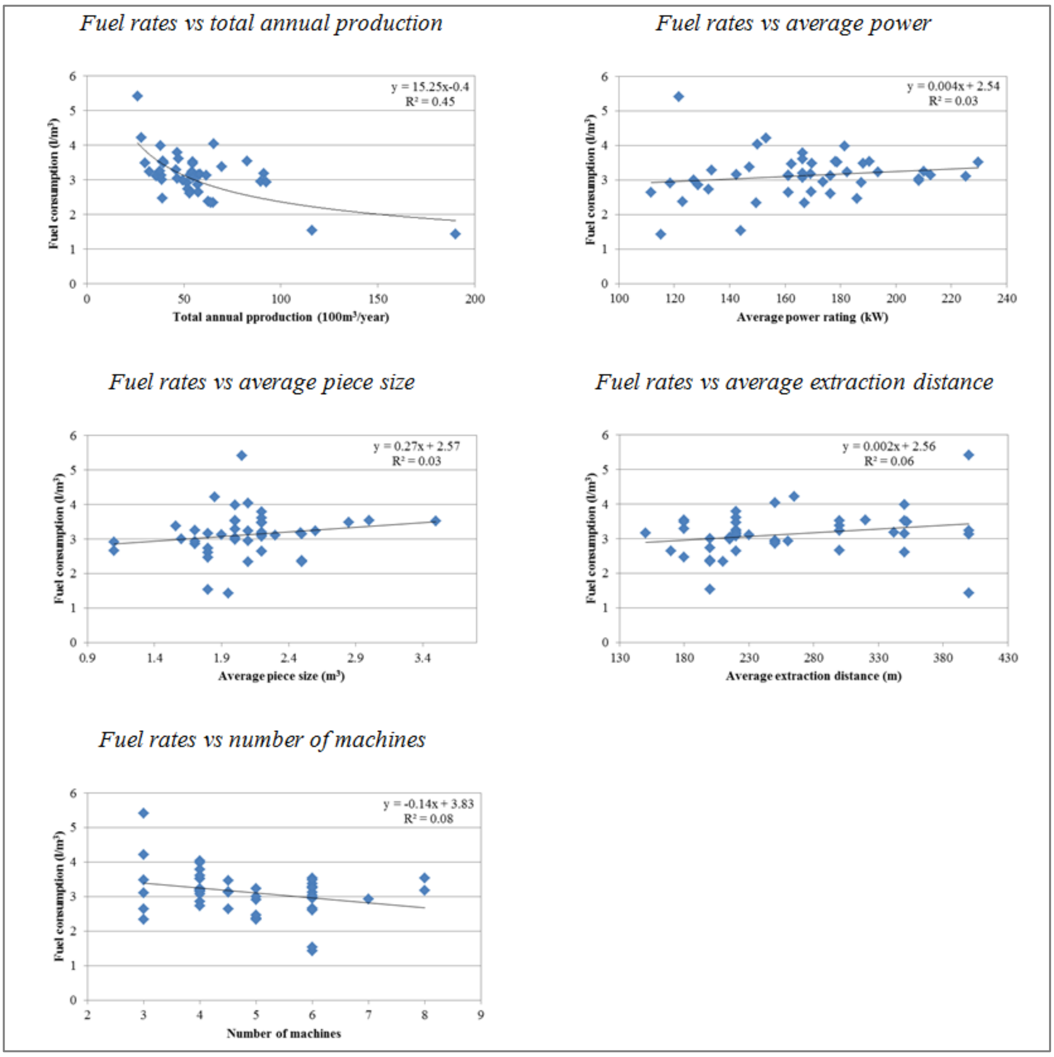

Figure 25: Linear and power function relationships of rates of fuel use in l/m^3

There was a general decreasing trend in average rates of fuel consumption in l/kWhr with average power, number of machines used, average piece sizes and average extraction distances (Figure 26). However, there was an increased rate of fuel use in l/kWhr compared to decreasing trends in l/m^3 with total annual production. Fuel use in l/kWhr showed a strong correlation for decreasing rates of use with average power rating (R^2=0.50), and number of machines used (R^2=0.22), average piece sizes handled (R^2=0.005) and average extraction distances (R^2=0.006), unlike with total annual production (R^2=0.10) where rates of fuel use in l/kWhr tended to increase with increase in total production. Larger machines tended to be more fuel efficient at higher power ratings and therefore logging crews should focus on using larger specialised logging machines for economics of scale with the shift towards mechanisation for steep terrain logging. ANOVA tests at 95% level of confidence (α=0.05) showed that rates of fuel use in l/kWhr were significantly different with number of machines used (p-value=0.01), and average system power (p-value<0.0001). However, rates of fuel use in l/kWhr were not significantly different with average piece size (p-value=0.73) and average extraction distance (p-value=0.68).

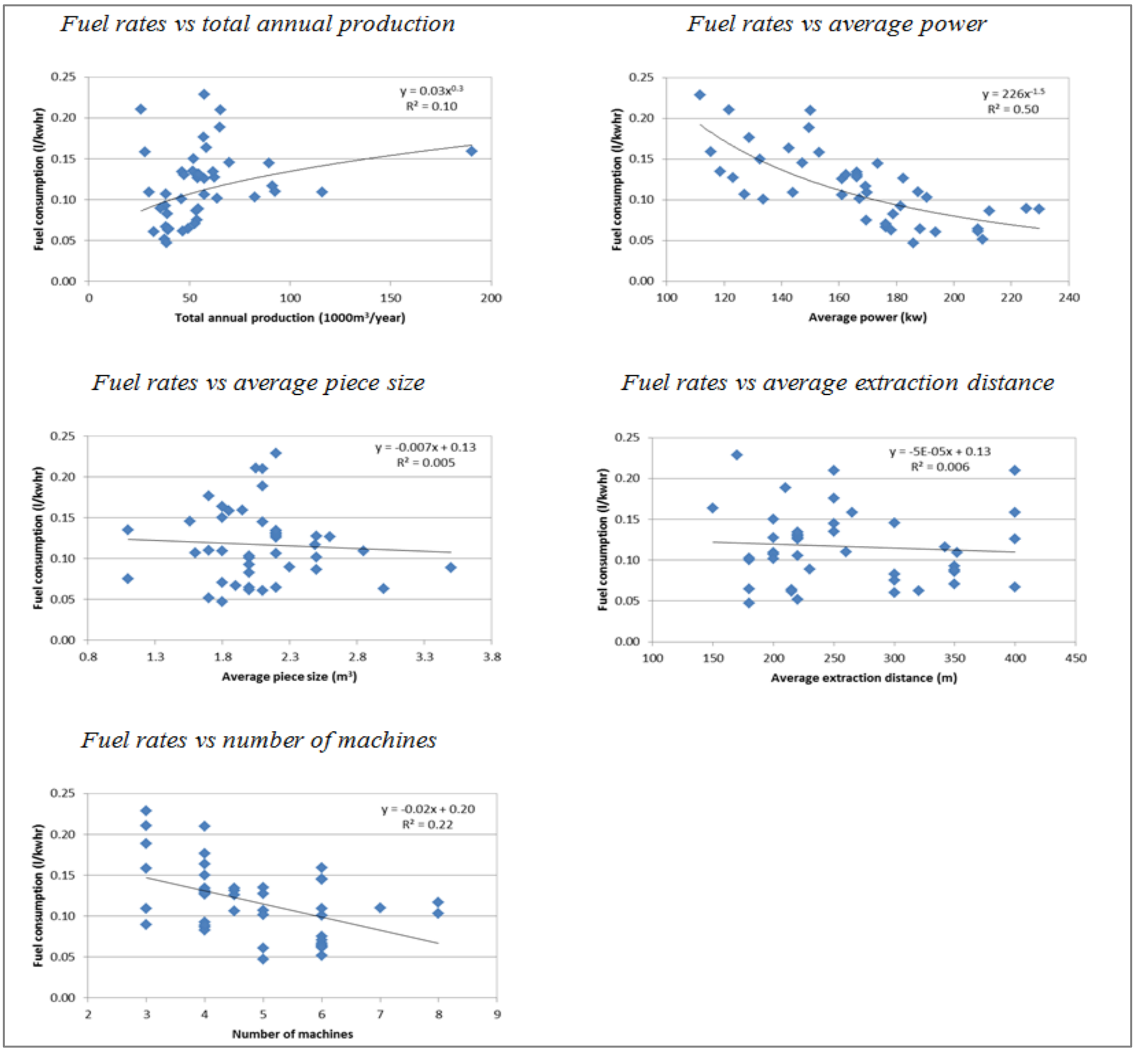

Figure 26: Linear and power function relationships of rates of fuel use in l/kWhr

4.6 Productivity and fuel consumption relationships by harvesting system

The average rates of fuel use for GB harvesting systems showed a decreasing trend with an increase in total annual production (R^2=0.68) (Figure 27). Therefore, focusing on higher production targets is important to achieving reduced rates of fuel use for GB harvesting crews.

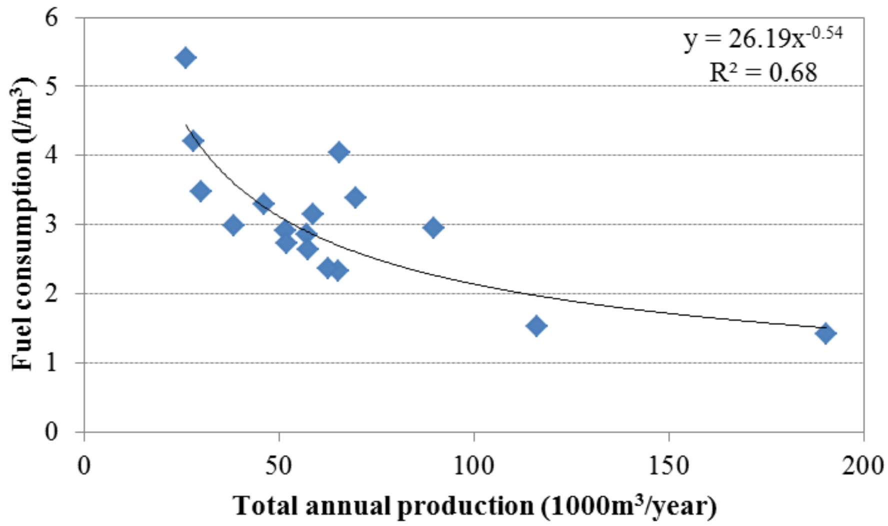

Figure 27: Fuel consumption relationships with total annual production for GB systems

The decrease in average fuel consumption rates for CY harvesting systems however, did not show a strong correlation with an increase in total annual production (R^2=0.04) (Figure 28). This indicated that cable yarding crews enjoy minimal economics of scale at high production compared to GB crews.

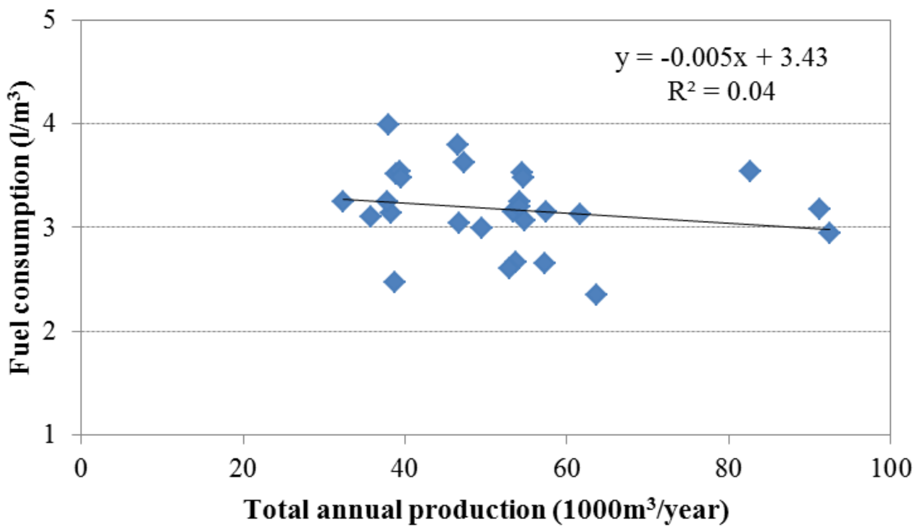

Figure 28: Fuel consumption relationships with total annual production for CY systems

4.6.1 Fuel use and scale of production (New Zealand and Southern US GB crews compared)

Average fuel consumption rates for ground-based operations in New Zealand reduces with higher scale of production (R^2=0.68). However, the average rates of fuel use for the Southern US do not seem to reduce with an increase in total production (R^2=0.05) (Figure 29). GB operations in New Zealand are executed on flat and rolling slopes, whereas, GB operations in the Southern US are generally conducted on flat and mildly rolling slopes as shown by data collected by Smidt and Gallagher (2013), Kenny et al. (2014), and Greene et al. (2014) over the previous years. There was no data on logging fuel use and production for CY operations from the Southern US for comparison with New Zealand CY systems in the study.

Differences in rates of fuel use between the two regions was attributed to differences in number of log products harvested as GB operations in New Zealand produce up to 17 log grades (Visser, 2013) compared to only three log grades of sawn timber, pulp and structural logs produced by the southern states USA (Kenny et al., 2014). Variability in tree species harvested from various production forests also contributed to differences in rates of fuel use between the Southern US and New Zealand systems. For example, in New Zealand, production forests are mainly composed of radiata pine (*Pinus radiata*) (Tolan & Visser, 2015), while southern yellow pine is common with the Southern US production forests (Smidt & Gallagher, 2013). The Southern US have also fully embraced mechanised logging operations compared to New Zealand GB operations where, for example this study data contained only 59% fully mechanised and 24% manual operations with the rest existing as hybrids of manual and mechanised types of systems.

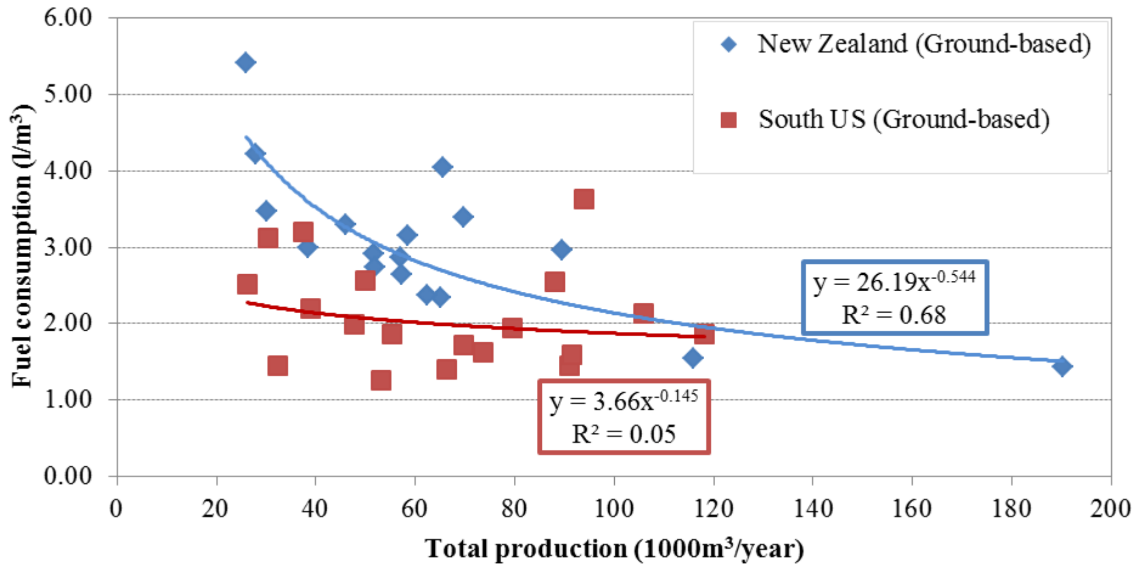

Figure 29: Rates of fuel use and total annual production for New Zealand and South US GB crews compared

4.7 Model for estimation of fuel consumption rates

Based on the size of the study dataset, the following linear regression model was developed through stepwise regression command in R statistical software to predict rates of fuel use in l/m^3 from the sample size of 45 harvesting systems. The data represented normally distributed and independent variance of response variable (rates of fuel use in l/m^3). Rates of fuel use in l/m^3 were predicted from total production, average extraction distance and slope of the harvesting site as predictor variables with R^2=0.47 and Akaike Information Criteria (AIC) = - 62.51.

$$\boldsymbol{Y\ (Response) \sim 2.64 - 1.2*10^{-5*}PRD + 2.8*10^{-3}ETD + 0.69*SLP\ (Steep) + 0.43*SLP\ (Rolling)}$$

Where *Y* is the rate of fuel use in l/m^3 and a y-intercept (2.64), SLP (steep) = 0 when GB and SLP (rolling) = 0 when CY. The coefficients of linear slopes for rolling sites represent GB while that for steep slopes represents CY operations. The rates of fuel use in l/m^3 from the model prediction were compared with actual rates of fuel use from the original data. There was 52% correlation between the predicted rates of fuel use in l/m^3 with model and the actual fuel use rates in the original study data (R^2=0.52) (Figure 30).

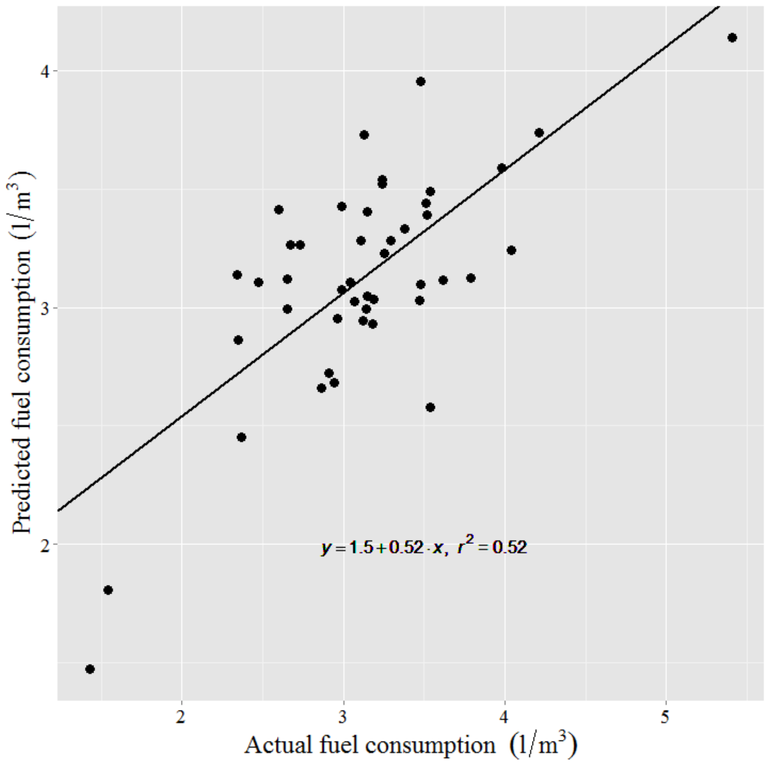

Figure 30: Predicted versus actual fuel consumption rates in l/m^3 for all the study data

The following linear model was also developed through step regression to predict the rates of fuel use in l/kWhr with total production, number of machines used, average power in kilowatt, slope, and directions of pulling from the complete study dataset with R^2=0.82 and Akaike Information Criteria (AIC) = - 347.08. The data used in model development for prediction of rates of fuel use in l/kWhr (response variable) came from normally distributed and independent variance.

$$X\ (Response) \sim 0.25 + 9.5*10^{-7}*PRD - 0.018*MAC - 7.35*10^{-4}*PWR + 0.08*SLP\ (Rolling) + 0.06*SLP\ (Steep) - 0.04*DRP\ (Uphill) - 0.05*DRP\ (Variable)$$

Coefficients of SLP (rolling) = 0 when CY systems and SLP (steep) = 0 when GB systems

Comparatively, there was 85% correlation between predicted and actual rates of fuel use in l/kWhr from the model (R^2=0.85). This was an indication of the appropriateness of model in reasonably predicting rates of fuel use in l/kWhr given the dataset used for development (Figure 31).

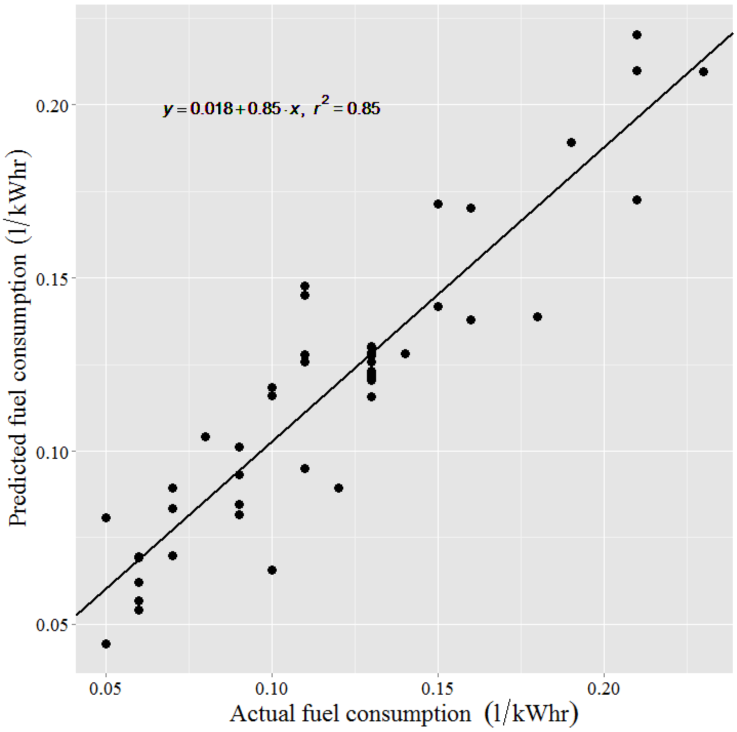

Figure 31: Predicted versus actual fuel consumption rates in l/kWhr for all the study data

4.8 Estimates of fuel use rates from logging costing models

There were observed differences in rates of fuel use in l/kWhr estimated using existing logging costing models and the actual rates of fuel use determined using study data (Table 33). LIRO model was 7% and 22% (Alastair, 1994) higher than the actual rates of fuel use from the survey by GB and CY operations, respectively. Miyata model (Miyata, 1980) showed a 7% underestimation of actual fuel use rates in l/kWhr by GB systems and also overestimated the actual rates of fuel by CY systems by 36%. Bilek (2009b) model underestimated the average rates of fuel use in l/kWhr for GB systems in the study by 27%, and at the same time overestimated rates of fuel use in l/kWhr by CY harvesting systems by 22%. The variability in the average rates of use determined with study data using these models were attributed to differences in terrains, and type of operations specific to countries of data collection and machine models used. The rates of fuel use obtained from the survey showed an improvement in logging mechanisation and could be used for updating LIRO costing schedules developed from older machine models of the 1980s, which are currently being used by logging contractors in New Zealand for various costing purposes.

Table 33: Fuel use rates from the study (bold and italic) and costing data compared

Costing model (Author)	Estimates (l/kWhr)	Difference from survey (%)
Study (GB system)	***0.15***	***Base case (survey)***
Study (CY system)	***0.09***	***Base case (survey)***
LIRO Model (Alastair, 1994)	0.16	7% (GB)
LIRO Model (Alastair, 1994)	0.11	22% (CY)
Miyata Model (Miyata, 1980)	0.14	7% (GB), 36% (CY)
Bilek Model (Bilek, 2009b)	0.11	27% (GB), 22% (CY)

4.9 Percentage of fuel costs in unit harvesting costs

The percentage of fuel costs in unit harvesting costs were determined using the rates of fuel use in l/m^3 (3.04 l/m^3 for GB systems and 3.18 l/m^3 for CY systems) from the study annual benchmarking data on unit harvesting costs of \$25.30/m^3 for GB and \$35.13/m^3 for CY (Visser, 2013) and diesel prices of \$1.51 per litre for the year 2013 (NZMBIE, 2015). Results showed that at \$1.51 per litre of diesel, fuel consumption costs constituted between a minimum of 9% and a maximum of 33% (average of 16%) per unit cost of harvesting for GB operations. Similarly, fuel costs constituted between a minimum of 10% and a maximum of 17 % (average of 14%) per unit cost of harvesting for CY operations. Given the variability in rates of fuel use associated with harvesting seasons across the year, logging contractors are bound to harvest at constantly changing fuel prices (Figure 32), but with close monitoring and control of rates of use, wide variations in profitability would be contained through optimised operations.

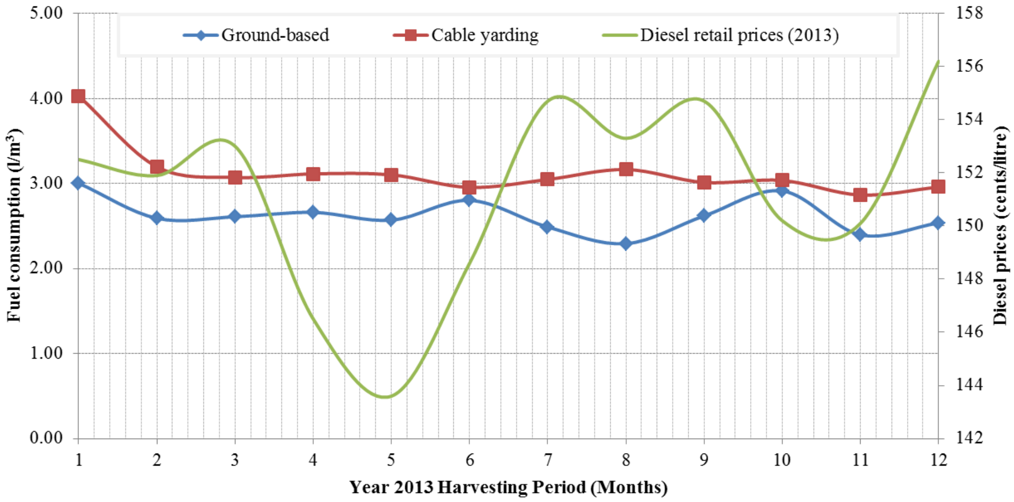

Figure 32: Average monthly fuel consumption for GB harvesting systems and diesel prices

4.9.1 Sensitivity analyses of fuel prices on harvesting costs

Sensitivity analyses for various diesel prices per litre of fuel showed that the percentage of fuel costs per unit of harvesting costs tended to increase with a corresponding increase in diesel prices for both GB and CY harvesting systems. These percentages of fuel costs reported in this study are specific to the data used and are subject to variability due to varying rates of fuel use by harvesting systems. For GB operations, assuming unit harvesting cost of $25.30/m^3 (Visser, 2013) subjected to increasing diesel prices, harvesting at maximum rates of fuel use (5.45 l/m^3) resulted in a steep increase in percentage of fuel costs per unit of harvesting costs in comparison to minimum rates of fuel use (1.43 l/m^3), and average rates of fuel use (3.04 l/m^3), as shown in Figure 33. Using CY systems unit harvesting costs of $35.13/m^3 (Visser, 2013) for various diesel prices, the percentage of fuel costs per unit of harvesting costs increased with an increase in diesel prices per litre (Figure 34). At maximum rates of fuel use (4.00 l/m^3), logging contractors risk a drop in profitability due to increased fuel costs per unit volume of timber harvested, compared to harvesting at minimum rates of fuel use (2.35 l/m^3), and average rates of fuel use (3.18 l/m^3).

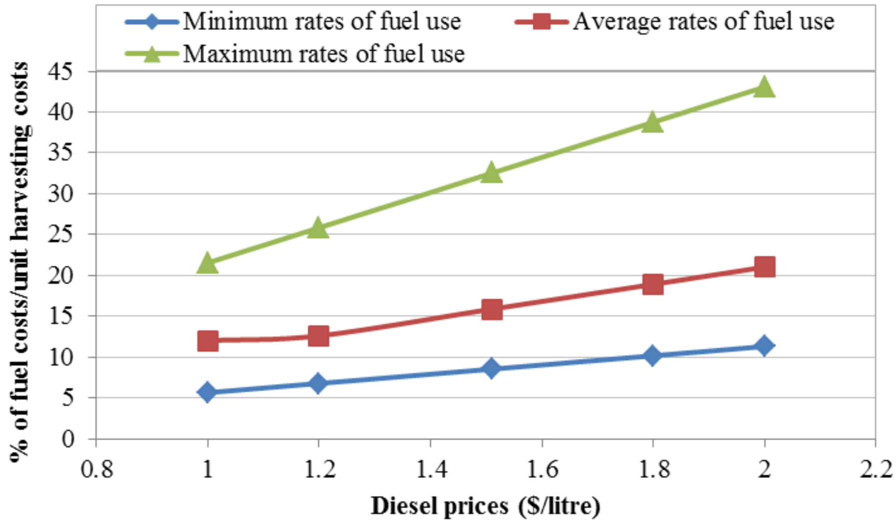

Figure 33: Estimates of proportion (percent) of fuel costs per unit harvesting costs with changing diesel prices for GB operations

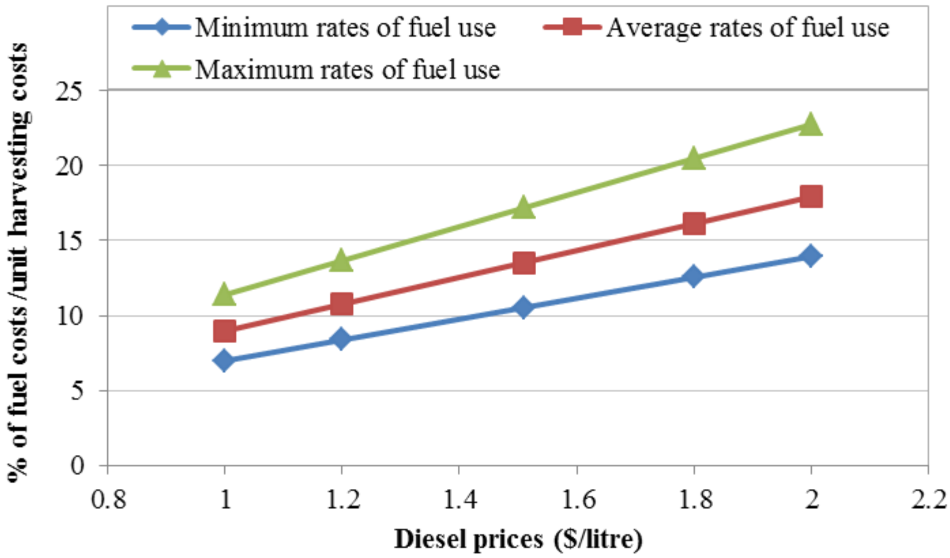

Figure 34: Estimates of proportion (percent) of fuel costs per unit harvesting costs with changing diesel prices for CY operations

Chapter 5: Discussion

Determining rates of fuel used by harvesting systems and machines appears easy since it involves dividing total fuel used by the total harvesting production or by total kilowatt-hours for the duration of the survey to compute rates of use in l/m^3 and/or l/kWhr. The only challenge in performing this simple arithmetic procedure is lack of readily available fuel use and production data and necessary harvesting attributes. In reality, obtaining data on fuel and production from logging contractors proved a difficult task during the survey given the sensitivity attached to the fuel use and production data by logging contractors. Data acquisition required the involvement of close and trusted industry and research partners as has been tried successfully in other countries during energy studies (Athanassiadis et al., 1999; Greene et al., 2014; Kenny et al., 2014; Sambo, 2002; Spinelli & Magagnotti, 2012).

Harvesting systems and fuel consumption

Results showed that on average, ground-based (GB) systems use 3.04 l/m^3 and cable yarding (CY) systems use 3.18 l/m^3 during normal harvesting operations. The differences in the average rates of fuel use in l/m^3 between the two harvesting systems were not significantly different. GB systems had a wide range of rates of use from 1.43 to 5.47 l/m^3 with more variability (31%) compared to the range of fuel use by CY systems (2.45 to 3.98 l/m^3) that showed a variability of 12%. The variability in rates of use between the two systems was attributed to differences in slope and directions of pulling towards a landing, surface conditions, average extraction distances, total production, number of machines used and average power rating, and level of harvesting system mechanisation.

The study results showed lower average rates of fuel use in l/kWhr for both GB and CY harvesting systems in comparison to rates of fuel use for machine costing schedules of 0.16 l/kWhr and 0.11 l/kWhr for GB and CY harvesting systems, respectively, developed for use in New Zealand by Alastair (1994). In comparison to previously published rates of fuel use in New Zealand, the study results showed a decrease in rates of fuel use over the years compared to the rates of fuel used in the 1980s (Gordon & Foran, 1980) and the 1990s (Alastair, 1994). Differences in rates of fuel use in l/kWhr between GB and CY harvesting systems was attributed to differences in average rates of production, number of machines used, average power rating, directions of pulling, average piece sizes and site slope.

Harvesting site characteristics and fuel consumption

Ground-based operations were conducted on flat and rolling slopes with rates of use in flat sites lower compared to rates of use in rolling slopes. The effect of rolling slope was assumed to be two-fold for GB operations during extraction based on uphill pulling against the adverse gradient and pulling downhill on favourable gradient. For example, when loaded skidders are moving uphill, they face resistances due to opposing force of gravity while same loaded skidders when pulling downward, their motions are aided by the direction of motion with gravitational force. In skidding uphill, more force is required to overcome the opposing gravitational force, frictional force between the tyres and the ground, and the skidder payload (Janett, 1986). Thus machine operators respond by engaging lower gears and injecting more fuel into the combustion chamber as observed by Makkonen (2004), to generate more energy, to overcome the opposing resistances and skidder payload, and allow forward motion. Makkonen (2004), also reported that when skidding downhill, the forward motion of the skidder is due to payload (increased momentum) and gravitational aid, as the operators engage gear levers in free-wheel position resulting in fuel conservation as opposed to skidding uphill. There are also differences in rates of fuel use when skidding branched versus delimbed stems for the same extraction distances, with branched stems offering more resistances to forward skidder motion than delimbed stems.

Since all the CY operations in this study were conducted on steep slopes and stems or logs pulled uphill toward landings, the variability in the average rates of fuel use were narrowed down to the differences in the various cable yarding rigging configurations, two-staging operations and differences in total crew production. Cable yarding and GB crews that had two-staging operations showed higher average rates of fuel use compared to the crews that did not two-stage, due to use of additional machines. However, this study did not collect data on various cable rigging configurations used by all the CY crews as it was not part of its main objective.

However, during the study one crew keen on conserving fuel and related costs shared information on rates of fuel use between slack-line pulling and shotgunning configuration. The crew reported 1 l/m^3 reduction of fuel under normal allowable deflection when changing from slack-line pulling to shotgunning. During the outhaul with shotgunning, fuel consumption was observed by the crew to be almost negligible as the carriage moved through gravitational aid without fuel involved. The crew manager however, revealed that there was a growing discontent among the operators during the trials, as they viewed the modification in rigging as a manipulative strategy by management to add additional non-remunerable work of handling rigging ropes to the already demanding operator responsibilities. This scenario can be seen to signal the complex mix of cost reduction strategy by management versus the perceived work ideology of logging crews towards change. Such strategy requires prior operator exposure and training on positive work habits, towards achieving economic efficiency, since operators form pivotal roles in determining fuel economy and overall operational efficiency. Research on the various types of rigging configurations used in New Zealand has been done (Harrill & Visser, 2012), however, none has been conducted to verify rates of fuel consumption by individual rigging configuration.

Higher rates of fuel use were also observed to be associated with wet harvesting conditions compared to rates of fuel use observed for dry and moist conditions. Theoretically, wet conditions render soils surfaces slippery, loose, muddy, and with poor traction. Such wet surfaces result in muddy conditions associated with machines being stuck. Pulling stuck machines off muddy sites requires additional fuel and, as the process is only a salvage operation, fuel used to remove stuck machines from muddy conditions eventually counts in the overall harvesting production in terms of costs. Wet weather also hampers harvesting operations as crews occasionally stop production operations and wait for conditions to normalise. However, the data captured in the survey was based on yearly averages as opposed to real time study data, and it was not easy to establish any significant effect of wet conditions on average fuel use. Since productivity is the main driver of the rates of fuel use during harvesting, reduction in total production when pulling stuck machines off muddy sites also translate to an economic loss as was observed by Makkonen (2004).

Average extraction distances and fuel consumption

Even though tests of significance showed that annual average extraction distances do not significantly influence rates of fuel use, longer extraction distances were associated with increased rates of fuel use compared to shorter extraction distances. This was attributed to extracting constant payloads by the skidders and yarders at longer distances resulting in reduced crew production and increased average rates of fuel use. One contractor shared findings after comparing fuel consumption between cable yarding and uphill skidding operations at equivalent distances of 500 m. The contractor noticed that in one week, 500 litres of fuel was used by Berger T23 hauler when shotgunning with an ACME carriage, while a TigerCAT grapple skidder used an equivalent of 1400 litres of fuel over a similar period for similar production volumes. Shotgunning was also observed to be faster, more productive, required little or no fuel during the outhaul, and generally quicker in each cycle compared to skidding.

Logging production and fuel consumption

Significance tests showed that total harvesting production was the main driver of fuel use rates in l/m^3. GB operations showed higher rates of production than CY operations, however, t-tests showed that average production between GB and CY systems were not significantly different. The lower rates of fuel use by GB systems were attributed to higher payloads by skidders and easier terrain compared to lower yarder productivity for most CY operations. Research shows that GB are generally more productive than CY systems, due to higher payloads and an easier work environment associated with operations on flat slopes, compared to steep slopes for CY operations (Visser, 2013). Ground-based operations are also more productive due to shorter extraction distances and more payload than CY systems.

Logging contracts between contractors and landowners and/or forest management companies are based on net production delivered. However, there are several tasks associated with production of final log grades such as log optimisation and quality processes that require use of more fuel after during processing. For example, processing of more log grades is time consuming in terms of log selection and optimisation to generate high quality grades as per the customer specification, through further processing (Tolan & Visser, 2015). Since harvesting operations in New Zealand may also involve roadside salvage of windthrow sites with occasional two-staging operations, more fuel to volume ratio may be used, as salvage harvesting operations are associated with complex logistics and lose in productivity that impact on fuel use.

Striking a balance between achieving higher crew target volumes versus customer specified volumes in the cut-plan is one of the challenges faced by crews, as more log handling is energy intensive and eventually uneconomical, due to more fuel input and costs (Tolan & Visser, 2015). Furthermore, more log grades require more processing operations by processor machines resulting in increased fuel supply rates and use. It has been observed that more handling of single log grade into differentiated log lengths does not increase net crew production, but significantly impacts on fuel consumption during handling. Studies by Tolan and Visser (2015) further showed that increasing number of log grades beyond nine (9) does not translate to marginal returns, but more fuel is still used during processing as GB and CY systems produce up to 17 log grades in a single operation in New Zealand (Visser, 2013).

Machines, average power rating and fuel consumption

The study also showed that decrease in average fuel consumption rates associated with increase in the number of machines used during harvesting, but the rates of fuel use begun to increases when more than 5 machines were used by any of the harvesting systems. These finding are consistent with results reported by Athanassiadis et al. (1999). However, in this study, CY systems used more number of machines on average compared to GB systems, and this was a possible explanation for variation in average rates of fuel use between the two systems of harvesting. CY systems was also associated with use of tower and swing yarder machines at higher average power rating compared to skidders used during GB operations. Larger machines with higher power ratings have been observed to use more fuel compared to small and medium sized machines by Jiroušek et al. (2007). This explains increased average consumption by cable yarding machines since yarders have a higher power rating compared to skidders used in GB systems as also reported by Ghaffariyan and Brown (2013) and Miyata (1980) on engine sizes and energy requirements. Variability in average fuel use due to differences in power rating informed machine costing models by Miyata (1980), Alastair (1994) and Bilek (2009b) with power rating taken as primary determinant of rate of fuel use by machines.

Level of mechanisation and fuel consumption

Manual GB operations were observed to use higher rates of fuel compared to fully mechanised GB operation. This was attributed to low production rates by manual GB operations compared to higher productions by mechanised GB crews. The study data contained 59% mechanised and 24% manual GB operations. Survey data also contained 86% of CY operations that used motor-manual felling and mechanised processing compared to only 7% fully mechanised. Motor-manual felling dominated steep slope felling operations in New Zealand for the survey period and is it is more versatile according to Spinelli and Magagnotti (2012). Fully mechanised CY operations used lower rates of fuel compared to manual and mixed system CY operations. Fully mechanised CY operations used fuel at higher rates due to the use of feller-bunchers and/or harvesters that required more fuel compared to fully motor-manual chainsaws. Level of mechanisation for processing for both GB and CY systems were observed to be in the increase compared to annual benchmarking harvesting data (Visser, 2015).

The rates of fuel use were also determined by whether processing was manual or mechanised. Cable yarding systems with mechanised processing required machines that used fuel at higher rates than motor-manual processing with chainsaws. Crews can adopt different configurations of both manual and mechanised felling and processing, but it is important to note that these different configurations are associated with use of fuel at different rates, and more focus should be on the most optimum configuration for any given harvesting site. In general, the level of mechanisation based on data contained in this survey depict New Zealand as being in the process of becoming fully mechanised, but still lagging behind in comparison to level of logging mechanisation in Sweden, Canada, and Finland. Full mechanisation of steep slope harvesting has also been viewed as a means of attaining logging efficiency due to reduced number of machines informed by increased safety concerns for operators (Visser et al., 2014). Reduced number of machines translates to reduced fuel supply and use by a single harvesting system as has been reported by Lindholm and Berg (2005).

Fuel consumption from literature and study results compared

Average rates of fuel use presented in the literature were found to vary with countries of data collection, type of cut (i.e. whether clear-cutting or thinning), number of machines used, harvesting seasons, and target log products for the market. In comparison, most clear-felling logging operations in New Zealand involved cut-to-length systems conducted on steep slope forests by CY harvesting systems or flat and rolling slopes by GB harvesting systems, which are potential sources of variability in rates of fuel use. Ground-based systems in New Zealand were also found to use higher rates of fuel on average compared to rates of fuel used by clear-cutting GB systems reported by Sambo (2002), Smidt and Gallagher (2013), Greene et al. (2014), and Baker and Greene (2012). These differences in average consumption rates between New Zealand GB systems and results in the literature were attributed to differences in regional landscapes defining their harvesting site slopes. For example GB operations in New Zealand are mostly conducted on flat to rolling slopes using 4.5 machines on average, compared to operations on mostly flat slopes with an average of three machines (harvester, skidder, and loader) in the Southern US as reported by Smidt and Gallagher (2013) and Kenny et al. (2014).

New Zealand harvesting operations also produce up to 15 log grades all processed in a single operation (Tolan & Visser, 2015) in comparison to mainly three log grades of pulp, saw-logs and structural logs and occasionally chipping material in the Southern US as reported by Kenny et al. (2014). Furthermore, the study data contained only 59% of GB operations in New Zealand that were fully mechanised with most crews using manual felling and mechanised processing interchangeably compared to GB operations in the Southern US where felling and processing are fully mechanised. Increased mechanisation is also associated with use of fewer machines which is a pointer to fuel saving. Having fewer machines on site for example, a self-levelling feller-buncher that specialises on felling and bunching and, at the same time processing of logs uses low quantities of fuel compared to having every single machine for felling and processing operations that are associated with higher fuel consumption.

The average power in kilowatt for the GB machines from the survey were also found to fall within the range of power ratings published by FORME (2012) machine data. However, FORME (2012) machine data was derived from standard logging operations scheduled for 8 hours daily for 175 annual logging days, unlike the GB crew used in the analyses in the study that had varied individual machine scheduled hours with operations running up to 247 days a year. FORME (2012) publication showed clear differences in annual SMH with survey data. Survey attributes indicated that under normal operational conditions, logging crews overworked machines above standard FORME (2012) schedules, translating to use of more fuel as was similarly reported by Gordon and Foran (1980).

Logging costing models and fuel consumption estimation

Use of LIRO and common machine costing spreadsheets in New Zealand (Alastair, 1994) assumed that GB and CY machines used fuel at the same rates irrespective of differences in harvesting site factors and machines used. The spreadsheet relies only on power rating in determining rates of fuel use by harvesting system. This model consistently ignores the effect of harvesting site factors such as slope and soil moisture conditions that were shown to significantly affect rates of fuel use in the study. Similarly, published FORME (2012) machine data assumes similar harvesting site factors of stand and terrain, and equal number of SMH and days worked annually. Use of FORME (2012) machine data and Alastair (1994) costing models for logging operations in New Zealand offer good indicators of possible rates of fuel use for various machines working under ideal forest conditions. However, assuming that these two models are accurate in predicting actual fuel use estimates for machines working on different harvesting sites for planning may lead to underestimation or overestimation of operational costs, therefore making optimum returns difficult to determine by the logging contractors.

Rates of fuel use in l/kWhr in this study are lower than the standard rates of fuel use developed for machine costing spreadsheets by Alastair (1994) and results of the fuel study reported by Gordon and Foran (1980). These low fuel use rates by current logging machines confirm the gains made through mechanisation of steep terrain logging over the last three decades in New Zealand. Results by Gordon and Foran (1980) showed that larger cable haulers commonly in use during the 1980s in New Zealand for CY operations used fuel at higher rates compared to fuel use in the study results on CY operations. This could be associated to increased logging mechanisation in New Zealand over the years with use of more efficient machines on energy consumption. There is therefore, need to update the rates of fuel use in l/kWhr in machine costing spreadsheets developed by Alastair (1994), to be consistent with rates of fuel use for current harvesting systems and machines given that the data was obtained from current machine models under New Zealand harvesting conditions. The model developed in the study for predicting rates of fuel use in l/kWhr also showed 85% correlation between predicted and actual rates of fuel use which is a good indicator for adjustment of current machine costing spreadsheets.

Fuel price sensitivity analyses and fuel consumption costs/proportion

In the literature review, most logging costing models used for determination of fuel use rates are specific to their countries of data collection (Pierre et al., 2014). Therefore, as a step towards achieving operational efficiency, it is important to conduct machine costing and estimation of rates of fuel use with data collected under harvesting conditions specific to a country of data collection. This provides logging contractors with the opportunity to estimate, with confidence, the rates of fuel use by systems and machines based on prevailing harvesting conditions to New Zealand. Moreover, most of the models reviewed in the literature consistently underestimated or overestimated fuel use rates in l/kWhr for New Zealand conditions.

From sensitivity analyses, the proportions of fuel use rates in terms of costs per unit logging rates for GB operations ranged between 9 and 33%, while that of CY operations ranged from 11 to 17% in New Zealand, based on logging rates in benchmarking data by Visser (2013). Increase in unit price of fuel at constant logging rate resulted in a corresponding increase in the proportion of fuel costs in unit harvesting cost. Fuel consumption monitoring and effective control by logging contractors is necessary for the realisation of economic viability through operational efficiency, due to the ever rising fuel prices.

Chapter 6: Conclusion

6.1 Conclusions

The study objective of determining rates of fuel use in l/m^3 and l/kWhr setting a benchmark for harvesting systems for New Zealand ground-based (GB) and cable yarding (CY) systems was achieved. Ground-based and CY harvesting systems use an average of 3.04l/m^3 and 3.18l/m^3, respectively under harvesting conditions specific to New Zealand. T-tests for differences in average rates of fuel use between GB and CY were however, not significantly different. This was a clear indication that on average, GB and CY harvesting systems use similar rates of fuel during harvesting. ANOVA tests at 95% level of confidence also showed that rates of fuel use in l/m^3 are not significantly different by type of harvesting systems chosen or used during operation. ANOVA tests also showed that rates of fuel use in l/m^3 were significantly different with total production, slope and direction of pulling during extraction. However, rates of fuel use in l/m^3 were not significantly different with number of machines used, average power, piece size, and surface moisture conditions. ANCOVA tests also showed that differences in rates of fuel use were dependent on uphill or variable direction of pulling during extraction and or whether a crew was operating on rolling or steep slope harvest site. Based on these statistical results, the study therefore concludes that the average rates of fuel use by GB and CY harvesting systems are the same and is dependent on total production, slope of harvesting sites and directions of pulling during extraction.

On another perspective, fuel consumption rates per unit of power rating by GB harvesting systems was 0.15l/kWhr while that by CY harvesting systems was 0.09l/kWhr. T-tests for the differences in average rates of fuel use in l/kWhr between GB and CY harvesting systems showed that the rates of fuel use in l/kWhr between GB and CY harvesting systems were significantly different. ANOVA tests at 95% level of confidence showed that the rates of use in l/kWhr were also significantly different with the type of harvesting system used, total production, number of machines used during the operations, average system power, slope of harvesting site, direction of pulling during extraction, and surface moisture conditions. ANCOVA tests further showed that rates of fuel use in l/kWhr were significantly different with uphill direction of pulling and steep slope. The null hypothesis that rates of fuel use between GB and CY harvesting systems is similar was rejected as there was enough evidence from the data collected that the rates were dependent on existing terrain and stand variables specific to each harvesting site and machines used. This study therefore concludes that rates of fuel use in l/kWhr are influenced by the type of harvesting system used (whether GB or CY), total production, number of machines used during the operations, average power, slope, directions of pulling during extraction and surface moisture conditions at the time of harvesting.

From the literature review, the rates of fuel use by GB crews in New Zealand were found to be higher than those of Canada, Sweden, and Finland. The average rate of fuel use by all the GB harvesting systems in New Zealand combined was also found to be 32% higher than the average rate of fuel use for similar GB harvesting systems of the Southern USA states of Alabama, Georgia, Florida, and North Carolina combined. The differences in the rates of use from study data, rates reported in literature, and comparisons with data from Southern USA were attributed to differences in level of logging mechanisation. The study found out from literature presented that steep terrain logging operations in New Zealand are still dominated by use of motor-manual and mechanised machines compared to fully mechanised operations of Southern US states, Canada, Sweden, and Finland. New Zealand GB crews also concentrate on producing more log grades, use more machines on average, and operate on terrains with high variability in slope. These defences makes New Zealand logging operations to be seen as using higher rates of fuel use on a global front.

Study significance and contribution to logging industry

Rates of fuel use by GB ($3.04 l/m^3$) and CY ($3.18 l/m^3$) systems can be used as benchmarks by logging contractors and stakeholders for harvesting systems and machine selection during harvest planning. Similarly, the rates of fuel use in l/kWhr determined from the study can also be used to update the existing machine costing spreadsheets by Alastair (1994), currently used in New Zealand. This is because the rates have been derived from data obtained under harvesting conditions of New Zealand. Following the sensitivity analyses performed using diesel prices for 2013 and harvesting benchmarking data (Visser, 2013), fuel consumption rates in New Zealand constitute between 9 and 33% and between 11 to 17% of unit harvesting costs for GB and CY operations respectively. This variability (percent) in fuel costs per unit harvesting cost can be used as benchmarks for adjustment of unit harvesting costs during changes in fuel prices. It is therefore imperative that logging contractors and landowners monitor their fuel consumption as changes in fuel price indices in New Zealand affect logging profitability. Furthermore, reporting rates of fuel use relative to unit of production was found to provide a robust measure of monetary comparison of harvesting costs between harvesting systems and machines used locally and internationally as opposed to use SMH, PMH, and/or kWhr units as denominator in fuel reporting.

6.2 Study limitations

One limitation of the study was comparing the rates of fuel use using yearly data as opposed to real time study data. As such the harvesting factors, such as terrain and stand attributes provided in the data, were assumed as standard across the year irrespective of harvesting seasons. Similarly, logging contractors were asked to provide data on harvesting attributes as annual averages: piece size, extraction distance, slope, direction of pull and surface moisture conditions. These were limitations, as harvesting crews normally move to new harvesting sites that have different site factors. For CY systems no data was gathered on the rigging configuration used. Harrill and Visser (2012) show that CY crews use different rigging configurations in New Zealand, and different rigging configuration are known to have different fuel use rates.

Production values reported for all the crews in the study only reflect the volumes of merchantable log grades delivered to the customers. Similarly fuel used in the analyses was based on fuel supply data from crews on site and not the actual fuel used by machines or by harvesting system during the operations. These were limitations of the study as production and fuel used in deriving the rates of use for a given crew or system might not reflect the actual production handled or fuel used during the entire period for which it was reported. For example, harvesting may have been done earlier but deliveries to the customer done at a later date. Furthermore, processed and stacked log grades on the last day of the month may be delivered on the first day of a successive month. Production data will only indicate the delivered logs as the production of the month of delivery, which may be incorrect. Moreover, fuel delivered and stored on site, or fuel delivered to the harvest site on the last day of the month may also find its use in the next month or end up in service vans.

Machine analyses in this study were based on data obtained from a single fully mechanised, high production GB crew on a stemming operation. This was a single crew data and was not representative of all GB crews in New Zealand. Therefore the information presented on machines is limited in terms of broader application, and use of the findings may be suitable only for comparable GB crews under similar stemming operations.

Most logging contractors appeared to not have data on production and fuel use kept by machines; and for those with data kept by machines, there was no information on machine make and power rating to match the data supplied. For example, the basic information provided by the logging contractors was by type of machine such as harvester, grapple skidder, processor, and loader without basic machine specification. This prompted the use of machine data by FORME (2012) to determine average machine power rating based basic machine description provided by the contractors. This was considered a limitation as some machines were assigned assumed power rating.

Finally, there was not an equal representation of logging crews based on the approach adopted for the study that targeted only willing logging contractors following non-response of company management to share data on their fuel use. There were more CY crews and systems (28) in the analyses compared to those of GB operations that were only 17, though the general distribution across New Zealand showed a good spread.

6.3 Recommendations for future research

Production and fuel supply information for individual crews available from accounts and management offices do not capture the actual consumption trends by a given harvesting system and individual machine as they are only relied on as surrogates for logging calculations. Therefore this study suggests a time study on production and fuel use specific to a given harvesting system and selected machines to establish the actual rates of use based on prevailing site conditions. Real time data on production and fuel use for a given harvesting system can be used to model fuel consumption relationships specific to given harvesting sites whose terrain and stand factors are predetermined.

Comprehensive studies on rigging configurations have been done in New Zealand (Harrill & Visser, 2012), therefore further research is needed to establish how rates of fuel use vary with different cable yarding rigging configurations. This is important in understanding the drivers of variability in rates of fuel use between the various CY crews and is a step towards attaining efficiency through the use of the most fuel efficient rigging configuration.

The responsibility of logging contractors to keep proper records on fuel use and production data by machines and harvesting systems is imperative towards achieving operational efficiency in logging through a better understanding. Machine operator sensitisation and consultation in decision making on fuel saving methods, as suggested by Makkonen (2004) are equally important as they form a pivotal role in fuel economy. These approaches on sensitisation can be achieved through stakeholder forums or independent pilot surveys and studies targeting random logging crews across harvesting regions of New Zealand.

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Appendices

Appendix 1: University of Canterbury Logging Fuel Use Study 2014

Paul Oyier & Rien Visser

Introduction – Why Conduct Fuel Use Study?

Fossil fuel (diesel and/or petrol) forms the primary energy that is used in forestry for timber logging operations to power the various machines during felling, extraction, processing and loading. As harvesting operational managers, knowing fuel use by a given system and/or by machines during logging is important for operational planning and execution.

Furthermore, fuel consumption, and by extension fuel costs forms a significant proportion of unit harvesting costs ($/m^3), a fact that should be well understood by those tasked to manage logging operations. Unfortunately, fuel costs are governed by factors such as price changes, inflation, and sometimes government fuel subsidies, dynamics that are beyond the control of most if not all logging mangers.

Therefore, understanding how much we use during our logging operations is important towards achieving operational efficiency and economic viability as key components of our harvesting planning in order to manage our logging businesses optimally.

Needs and benefits to contractors of the fuel use study

1. We cannot control fuel prices at the pump yet price changes affect our profitability; but we can control how much we use for producing and/or handling a unit volume of timber by harvest methods and understand the variability between them.
2. Fuel use information will help us understand consumption by machines and the variability between them in terms of make, model and power rating. This will further broaden our knowledge on which machines are best in terms of fuel use and cost effectiveness.
3. Knowledge on fuel use will help understand how key stand and terrain variables: slope, surface conditions, extraction distance, direction of pull, and piece size interact, to have an overall effect on the quantity of fuel used to produce a unit volume of timber by system and/or by individual or group of machines.
4. Seasonal variations in fuel use are important as they help harvest planners to schedule machines to new tract areas, or to access timber from steeper terrain. Importantly, fuel use figures can help in adjusting consumption requirements by season.
5. The information can help in planning/decision making about harvesting system selection for any given site, the future impact on harvesting more remote and steep forests, and/or the effect of short term inflation in fuel prices on logging operations.
6. With fuel use information, we can project logging cashflows based on productivity by given machines and systems through a better understanding of our unit harvesting costs on a daily/weekly/monthly basis?

As a key reminder, the study guarantees confidentiality to the participating contactors and forest companies when they provide data on fuel use from their companies. No disclosure to third parties and/or other companies regarding the sources of data. Participants will also be regularly updated on study progress and key findings.

Appendix 2: Survey data collection sheet

School of Forestry / Logging System Fuel Use Study Data collection sheet

Crew Name: ____________

Total volume harvested in 2013: _________________ tonnes

Total fuel used in 2013: _________________ litres

(Note - if you have the production and fuel use data by month, please use next page)

Typical average piece size: ______ m^3

Typical average extraction distance: ___________ metres

Typical direction of pull: Mainly flat _____ Uphill ____ Downhill ____ *(tick one)*

Typical terrain: Mainly flat (0-15%) __ Rolling (15-30%) __ Mainly steep (>30%)__*(tick one)*

Typical surface Conditions: Dry_____ Moist____ Wet____ *(tick one)*

Approximate scheduled hours worked per day _______ and days per year _______:

Please fill in the make and model of each machine on site.

Machine	Type*	Make	Model	hp if known	Other info?
1					
2					
3					
4					
5					
6					
7					
8					

*Harvester, Extraction, Processing, Loader

Fuel Use by Month

Machine	Production (tonnes)	Fuel Used (litres)	Comments: i.e. weather events, machinery changes, system changes?
Jan			
Feb			
March			
April			
May			
June			
July			
August			
September			
October			
November			
December			

Thanks for your time!

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Appendix 3: Sample data from study participants

School of Forestry / Logging System Fuel Use Study

Data collection sheet.

Crew Name: Crew A.

Total volume harvested in 2013: 92530 tonnes

Total fuel used in 2013: 271,877 litres

(**Note -** if you have the production and fuel use data by month, please use next page)

Typical average piece size: 1.7 m^3

Typical average extraction distance: 260 metres

Typical direction of pull: Mainly flat ____ Uphill ✓ Downhill ____ *(tick one)*

Typical terrain: Mainly flat (0-15%) __ Rolling (15-30%) __ Mainly steep (>30%) ✓ *(tick one)*

Typical surface Conditions: Dry____ Moist ✓ Wet____ *(tick one)*

Approximate scheduled hours worked per day 8 **and days per year** 235 :

Please fill in the make and model of each machine on site.

Machine	Type*	Make	Model	hP if known	Other info?
1	Swing Yarder		TB6355		
2	Waratah	Hitachi	EX400		
3	Skidder	Cat	525C		
4	Bell				
5	Machine Faller	Climbmax			
6	Excavator	Hitachi	ZX280		
7	Backline	Hitachi	ZX330		
8	Guy Anchor	Hitachi	EX400		

*Harvester, Extraction, Processing, Loader

Thanks for your time!

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Fuel Use by Month

Machine	Production (tonnes)	Fuel Used (litres)	Comments: i.e. weather events, machinery changes, system changes?
Jan	5113	20413	
Feb	4575	15448	
March	4664	19864	
April	6438	22261	
May	9701	30467	
June	8085	22054	
July	10275	25814	
August	9846	29963	
September	9881	25530	
October	9905	27039	
November	9305	22831	
December	4742	10193	

Appendix 4: South United States Logger survey form

Crew name ____________________________ (will be kept confidential) State _______

Tract info: ______ acres **type cut:** _____partial _____clearcut

Please circle one **species**: mostly softwood mostly hardwood mix

on each of **slope**: 0% 0-15% 16-35% greater than 35%

these 3 lines: **moisture** : dry moist wet

Average diameter (inches) ______ Range of diameter________ ___ (such as 5” to 11”)

Equipment info:

Type*		Year, Make and Model	Fuel Use**
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
		System	_______

Total Volume __________

Circle one: tons

MBF

cords

other ________

Product types (percentages must add up to 100%)

Bolts______

Chips_______

Pulpwood________

Sawtimber_________

*type: list feller-buncher (FB), skidder (SK), knuckleboom loader (KL), processor (PR) ,chipper (CH), harvester (HA), forwarder (FW) or other (please give me a hint).

**fuel use: provide gallons consumed for individual machines if possible, or just list total system use on line at bottom

Appendix 5: INFORME Consulting machine data (FORME, 2012)

Machine	Type	Average Power (kW)	SMH	Annual SMH	Days/ Year	Fuel (l/SMH)	Fuel l/kWhr
Skidder (RT)	Winch	96	8	1400	175	10.59	0.11
Skidder (RT)	Winch	132	8	1400	175	13.44	0.10
Skidder (RT)	Grapple	125	8	1400	175	16.89	0.14
Skidder (RT)	Grapple	150	8	1400	175	18.87	0.13
Skidder (Tracked)	Winch	124	8	1400	175	19.63	0.16
Skidder (Tracked)	Grapple	124	8	1400	175	21.63	0.17
Loader (RT)	Front-end	82	8	1400	175	9.40	0.11
Loader (RT)	Front-end	110	8	1400	175	12.51	0.11
Loader (RT)	Front-end	155	8	1400	175	17.51	0.11
EXC loader	Grapple	104	8	1400	175	16.40	0.16
EXC loader	Grapple	125	8	1400	175	19.79	0.16
EXC loader	Grapple	156	8	1400	175	24.79	0.16
EXC loader	Grapple	200	8	1400	175	31.88	0.16
EXC Processor	22 tonne	104	8	1400	175	20.50	0.20
EXC Processor	35 tonne	200	8	1400	175	39.86	0.20
Feller-buncher	Self-levelling	200	8	1400	175	40.86	0.20
Forwarder	8 Wheel	145	8	1400	175	18.48	0.13
Forwarder	8 Wheel	175	8	1400	175	20.85	0.12
Tower Yarders	60tf	225	8	1400	175	20.29	0.09
Tower Yarders	86ft	338	8	1400	175	25.40	0.08
Swing Yarders	Small	240	8	1400	175	23.00	0.10
Swing Yarders	Large	335	8	1400	175	32.20	0.10
Excavator yarder	Used Base	200	8	1400	175	19.13	0.10
Excavator yarder	New Base	200	8	1400	175	15.03	0.08